NPS ARCHIVE
1960
LIU, C.

TRANSISTORIZED RELAY SERVO OPTIMIZATION USING A SERIES MOTOR

CHAO CHUAN LIU

LIBRA
NAVAL POST[illegible]E SCHOOL
MONTEREY, CALIF. 93940

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

TRANSISTORIZED RELAY SERVO OPTIMIZATION USING A SERIES MOTOR

* * * * *

Chao Chuan Liu

TRANSISTORIZED RELAY SERVO OPTIMIZATION USING A SERIES MOTOR

by

Chao Chuan Liu
//
Lieutenant (Junior Grade)

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN

ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

1960

NPS ARCHIVE
1960
LEU, C.

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIF. 93940

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

TRANSISTORIZED RELAY SERVO OPTIMIZATION USING A SERIES MOTOR

by

Chao Chuan Liu

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

from the

United States Naval Postgraduate School

ABSTRACT

The transistorized controller has been design and used in this experimental servo system instead of an ordinary vacuum tube amplifier and contactor relay. The series motor was used in the investigation.

It is the purpose of this paper to show by experimental means that the nonlinearity of the series motor in fact provides the necessary characteristic to permit transistorized relay servo optimization by the use of switching criteria base simply on lead network and error rate feedback control.

The effects on system response of different filters, different error rate feedback and various motor supply voltages were investigated. Dead beat response to any size step displacement input was found possible in properly adjusted the filter elements or control amount of negative error rate and error feedback for compensation as switching criteria.

The advice and assistance of Dr. George J. Thaler and instructor Richard Dorf of the U. S. Naval Postgraduate School are most sincerely appreciated.

TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	Experimental System and Transistorized Circuit Design	3
3.	Filter Design	14
4.	Transient and Frequency Response of Natural System with Position Error Feedback Control for Step Input	19
5.	Transient and Frequency Response of Natural System with Position Error and Negative Error Rate Feedback Control	29
6.	Transient and Frequency Response of Natural System with Positive Error and Positive Error Rate Feedback Control.	41
7.	Transient and Frequency Response of Natural System with Lead Network, Position Error, and Positive Error Rate Feedback Control.	50
8.	Comparison of Results	79
9.	Conclusions and Recommendations	92
10.	Bibliography	94

LIST OF ILLUSTRATIONS

Figure No.		Page
1.	Block Diagrams of Experimental System	4
2.	Schematic Diagram of Experimental System	5
3.	D. C. Amplifier Circuit	6
4.	The Transistorized Relay Circuits	8
5.	Bang-Bang, Dead zone, and combination Circuits	11
6.	Tachometer Calibration curve	12
7.	The Comparison of Transistorized Relay to Contactor Relay	13
8.	Lead Network Filter	15
9.	Transient Responses of System with Position Error Feedback for Large Step Inputs (1)	21
10.	Transient Responses of System with Position Error Feedback for Large Step Inputs (2)	22
11.	Phase Plane Trajectories of System with Position Error Feedback for Large Step Inputs	23
12.	Transient Responses of System with Position Error Feedback for Small Step Inputs (1)	24
13.	Transient Responses of System with Position Error Feedback for Small Step Inputs (2)	25
14.	Phase Plane Trajectories of System with Position Error Feedback for Small Step Inputs	26
15.	Frequency Responses of System with Position Error Feedback (1)	27
16.	Frequency Responses of System with Position Error Feedback (2)	28
17.	Transient Responses of System with Position Error and -0.01667 Error Rate Feedback (1)	31
18.	Transient Responses of System with Position Error and -0.01667 Error Rate Feedback (2)	32

Figure No.		Page
19.	Phase Plane Trajectories of System with Position Error and -0.01667 Error Rate Feedback	33
20.	Transient Responses of System with Position Error and -0.611 Error Rate Feedback (1)	34
21.	Transient REsponses of System with Position Error and -0.611 Error Rate Feedback (2)	35
22.	Phase Plane Trajectories of System with Position Error and -0.611 Error Rate Feedback	36
23.	Transient Responses of System with Position Error and -0.161 Error Rate Feedback (1)	37
24.	Transient Responses of System with Position Error and -0.161 Error Rate Feedback (2)	38
25.	Phase Plane Trajectories of System with Position Error and -0.161 Error Rate Feedback	39
26.	Frequency Responses of System with Position Error and Negative Error Rate Feedback	40
27.	Transient Response of System with Position Error and Positive Error Rate Feedback for Large Step Inputs (1)	42
28.	Transient Response of System with Position Error and Positive Error Rate Feedback for Large Step Inputs (2)	43
29.	Phase Plane Trajectories of System with Position Error and Positive Error R te Feedback for Large Step Inputs	44
30.	Transient Responses of System with Position Error and Positive Error R te Feedback for Small Step Inputs (1)	45
31.	Transient Responses of System with Position Error and Positive Error Rate Feedback for Small Step Inputs (2)	46
32.	Phase Plane Trajectories of System with Position Error and Positive Error Rate Feedback for Small Step Inputs	47

Figure No.		Page
33.	Frequency Response of System with Position Error and Positive Error Rate Feedback (1)	48
34.	Frequency Responses of System with Position Error and Positive Error Rate Feedback (2)	49
35.	Transient Responses of System with Filter 1, Position Error, and ositive Error Rate Feedback (1)	51
36.	Transient Responses of System with Filter 1, Position Error, and Positive Error Rate Feedback (2)	52
37.	Phase Plane Trajectories of System with Filter 1, Position Error, and Positive Error Rate Feedback	53
38.	Transient Responses of System with Filter 2, Position Error and Positive Error Rate Feedback (1)	54
39.	Transient Responses of System with Filter 2, Position Error, and Positive Error Rate Feedback (2)	55
40.	Phase Plane Trajectories of System with Filter 2, Position Error, and Positive Error Rate Feedback	56
41.	Frequency Responses of System with Filter 1 and 2, Position Error, and Positive Error Rate Feedback (1)	57
42.	Frequency Responses of System with Filter 1 and 2, Position Error, and Positive Error Rate Feedback (2)	58
43.	Transient Response of System with Filter 3, Position Error, and Positive Error Rate Feedback (1)	60
44.	Transient Response of system with Filter 3, Position Error, and Positive Error Rate Feedback (2)	61
45.	Phase Plane Trajectories of System with Filter 3, Position Error and Positive Error Rate Feedback	62
46.	Transient Responses of System with Filter 4, Position Error and Positive Error Rate Feedback (1)	63
47.	Transient Responses of System with Filter 4, Position Error and Positive Error Rate Feedback (2)	64
48.	Phase Plane Trajectories of System with Filter 4, Position Error and Positive Error Rate Feedback	65

Figure No.		Page
49.	Frequency Responses of System with Filter 3 and 4, Position Error and Positive Error Rate Feedback (1)	66
50.	Frequency Responses of System with Filter 3 and 4, Position Error and Positive Error Rate Feedback (2)	67
51.	Transient Responses of System with Filter 5, Position Error and Positive Error Rate Feedback (1)	68
52.	Transient Responses of System with Filter 5, Position Error and Positive Error Rate Feedback (2)	69
53.	Phase Plane Trajectories of System with Filter 5, Position Error and Positive Error Rate Feedback	70
54.	Frequency Response of System with Filter 5, Position Error and Positive Error Rate Feedback (1)	71
55.	Frequency Responses of System with Filter 5, Position Error and Positive Error Rate Feedback (2)	72
56.	Transient Responses of System with Filter 6, Position Error and Positive Error Rate Feedback (1)	73
57.	Transient Responses of System with Filter 6, Position Error and Positive Error Rate Feedback (2)	74
58.	Phase Plane Trajectories of System with Filter 6, Position Error and Positive Error Rate Feedback	75
59.	Transient Responses of System with Filter 7, Position Error and Positive Error Rate Feedback (1)	76
60.	Transient Responses of System with Filter 7, Position Error and Positive Error Rate Feedback (2)	77
61.	Phase Plane Trajectories of System with Filter 7, Position Error and Positive Error Rate Feedback	78
62.	Transient Responses of System with Position Error Feedback and Various Motor Supply Voltage of 400 cps A. C. (1)	80
63.	Transient Responses of System with Position Error Feedback and Various Motor Supply Voltage of 400 cps A. C. (2)	81

Figure No.		Page
64.	Comparison of Transient Response of System Using Various Motor Supply Voltage of 400 cps A. C.	82
65.	Transient Responses of System with Position Error Feedback and Various Motor Supply Voltage of 60 cps A. C.	83
66.	Comparison of Transient Response of System Using Different Negative Error Rate Feedback Control	85
67.	Comparison of Phase Plane Trajectories of System Using Different Negative Error Rate Feedback Control	86
68.	Comparison of Frequency Response of System Using Different Negative Error Rate Feedback Control	87
69.	Comparison of Transient Response of System Using Different Filter Compensation	89
70.	Comparison of Phase Plane Trajectories of System Using Different Filter Compensation	90
71.	Comparison of Frequency Response of System Using Different Filter Compensation	91

1. Introduction.

The transistorized relay servomechanism is a new field in automatic control systems. Due to its light weight, small, compact construction short relay time lag, and small dead zone, it will probably occupy a very important place in the future of industrial applications.

Most relay servomechanisms have a serious problem of contact arcing and time lagging. The use of silicon controlled rectifiers as ordinary relay can reduce these problems completely. Since there are no contactors on silicon controlled rectifier switches the arcing problem is automatically eliminated. The rectifier switch has only a few micro-seconds of turn on and turn off times so the switching lagging time may be negligible for general application. In addition to the above two principal advantages, the small dead zone and low forward gate voltage drop makes the silicon controlled rectifier relays approach ideal relay characteristics. Another advantage of the transistorized relay controller, is that the transistorized D. C. amplifier has compact construction and eliminates damage due to vibration and shock. It's weight and dimension is about one twentieth of conventional vacuum tube D. C. amplifiers. On the other hand, there are some disadvantages to transistorized servomechanisms. The transistor parameters vary either linearly or exponentially with absolute temperature. Thermal drifts can be compensated to some extent by inserting other temperature-sensitive elements in the circuit, but this calls for careful adjustment, and, if the compensating element has a thermal time constant different from that of the transistor, drifts will still occur while the ambient temperature is changing. So this characteristic makes it more difficult to design a

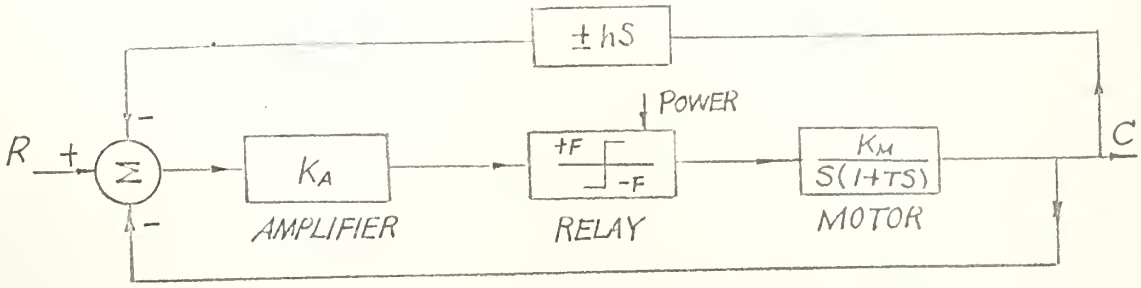
transistor D. C. amplifier than ordinary D. C. amplifier. In this experimental system, the matching transistor pairs were used for D. C. amplifier. They present a good characteristic for compensating bias changes which reduces the drift problem to a minimum. The experimental system which I chose was position servomechanism with error and error rate feedback control, using one series motor. With the purpose of achieving optimum response, different lead networks were used. The different electrical sources have been applied to this system in order to compare their responses.

2. Experimental System and Transistorized Circuit Design

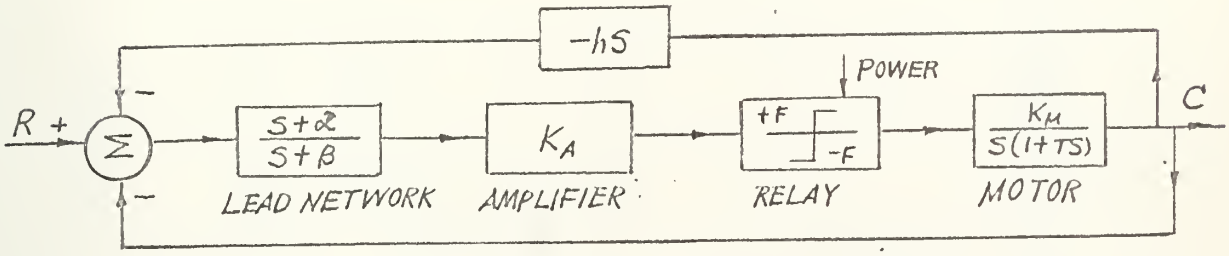
The experimental system is position control servomechanism with transistorized design amplifier and relay instead of ordinary vacuum tube amplifiers and a double throw polarized type relay. The block diagrams of the Experimental System are shown in Fig. 1. The transistors for the amplifier were 2N35, 2N34 matching transistor pairs and 2N229 for output stage. The "relay" block contains two C36A silicon controlled rectifiers. Their electrical circuit is shown in Fig. 3. The Oster series reversible motor was used in the investigation. It is type A-21E-12R, rated at 28 Volts d.c. and 0.4 amps. A reduction gear ratio of 236:1 was used between the motor and the output shaft. The load is ordinary three inches flywheel mounted on output shaft.

The source to operate silicon controlled rectifier and transistorized amplifier was 42 Volts d.c., from battery. The main power supply to motor was 400 cps and 60 cps 120 volts a.c. The variac and transformer was adjusted to get the testing applied voltages: 60, 70, 80, 90 Volts RMS on 400 cps and 40, 50, 60, Volts RMS on 60 cps.

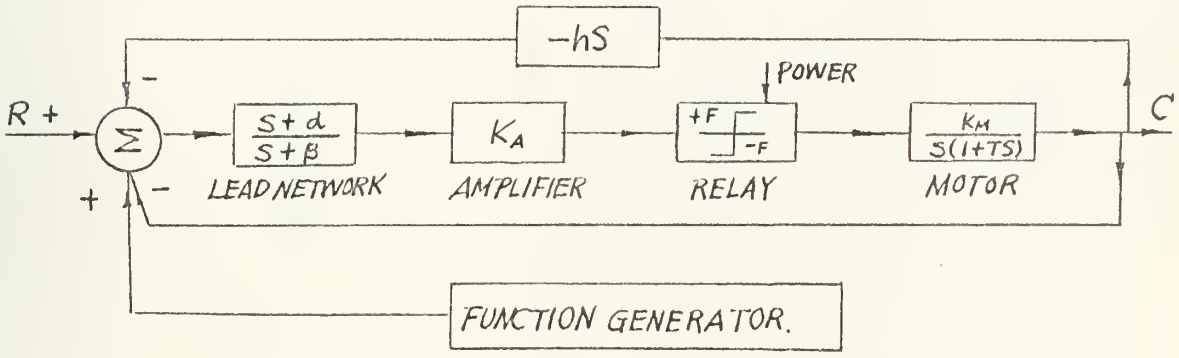
In Fig. 1(a) the block diagram shows the system used error and tachometer feed back control. The positive tachometer feedback has also been used with the purpose of making more oscillation in the transient response and then lead network was applied to compensate it. Fig. 1(b) shows the block diagram of positive error rate feedback circuit. Generally speaking, this type of system should never be built in this peculiar way, but for research purposes this type of connection was made in the experimental system. Fig. 1(c) shows the system relation when the frequency response is being tested. More details about the amplifier and



(a)



(b)



(C)

Fig. 1. BLOCK DIAGRAMS OF EXPERIMENT SYSTEM.

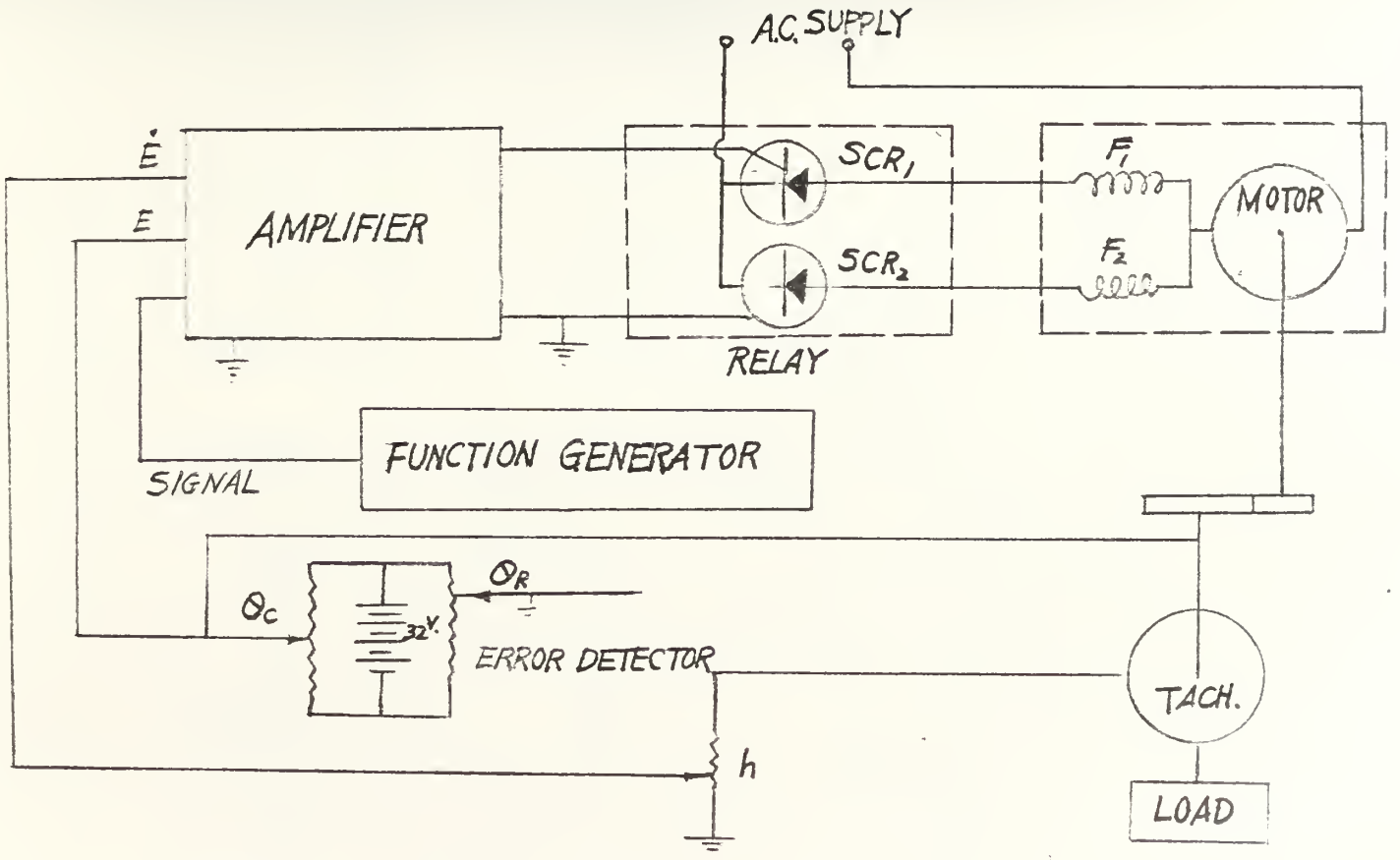


Fig. 2. SCHEMATIC DIAGRAM OF EXPERIMENTAL SYSTEM.

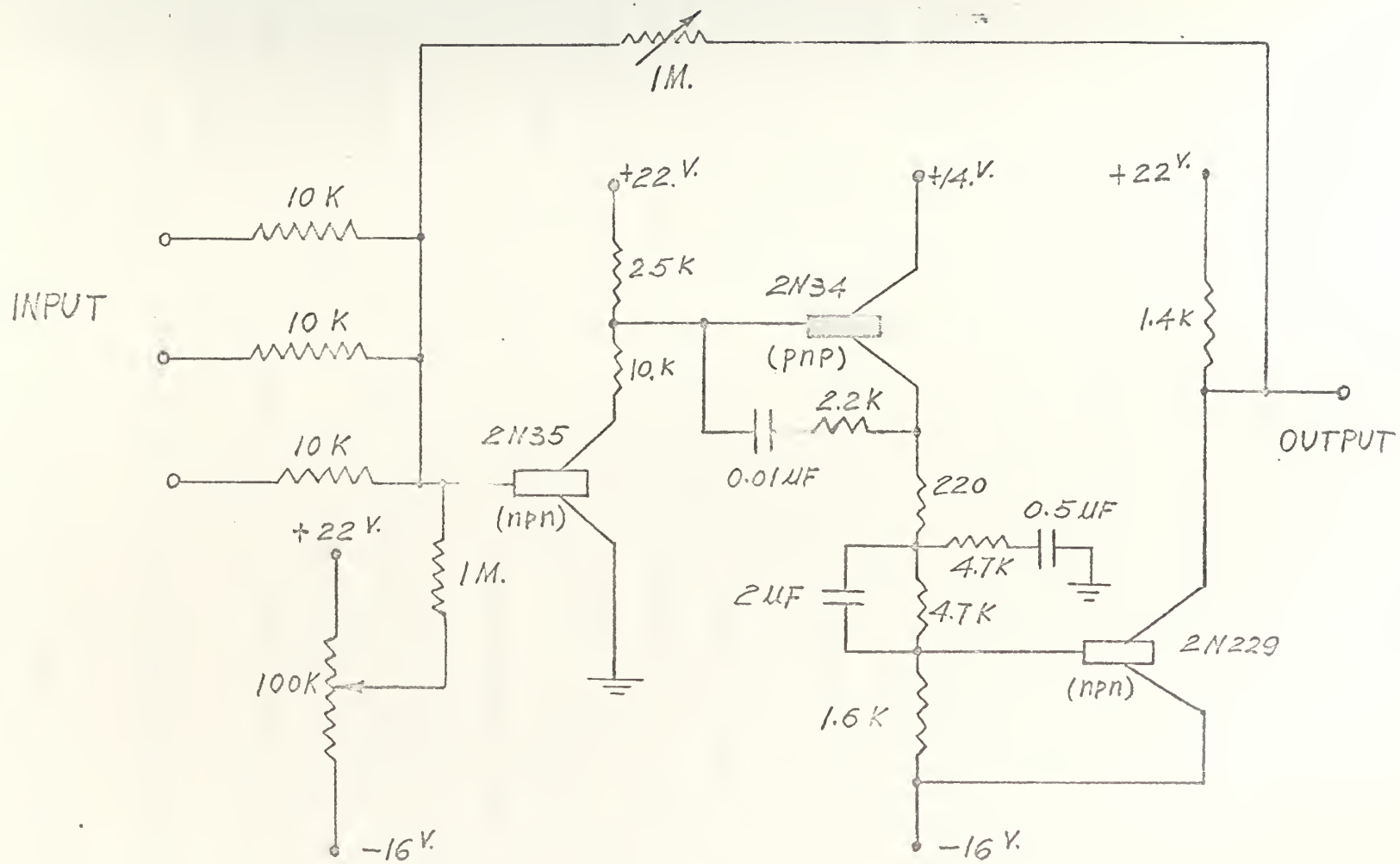


Fig. 3 D. C. AMPLIFIER CIRCUIT

the transistorized relay are shown in Fig. 3 and Fig. 4.

As described in the preceding introduction, the amplifier was built with three transistors, the matching pair transistors for the first and second state, the 2N 229 for the third stage of the amplifier. The gain of the amplifier can be adjusted by adjusting the bias resistance of the first stage or over-all feedback path resistance. The connection diagram of the amplifier is shown in Fig. 3. There are different methods of connection which enables the transistorized relay to work in this system. The best method is shown in Fig. 4(a). It has higher gate current to turn on the silicon controlled rectifiers, as compared to the second method of connection which is shown in Fig. 4(b). In Fig. 4(b), the gate current must pass through two field coils, therefore, the resistance of two field coils reduces the gate current considerably. In Fig. 4(c), the third possible method is shown, but power is wasted to produce heat in two field windings when no signal, gate voltage and gate current can come into the relay circuit. In other words, the system wastes power when the system is in a steady state. The solid line and dot line arrows show the direction of gate current flowed in different cases. Only one silicon controlled rectifier conducted power to the motor each time. When the system is in a steady state, both rectifiers are turned off. These three methods of connection have all been tested. All data presented in this thesis were obtained from the best method of connection, Fig. 4(a).

The general characteristics of silicon controlled rectifier C36A are listed on table 1.

In addition to the above 3 methods of using silicon controlled rectifier as a relay, there is yet another method which can be designed by

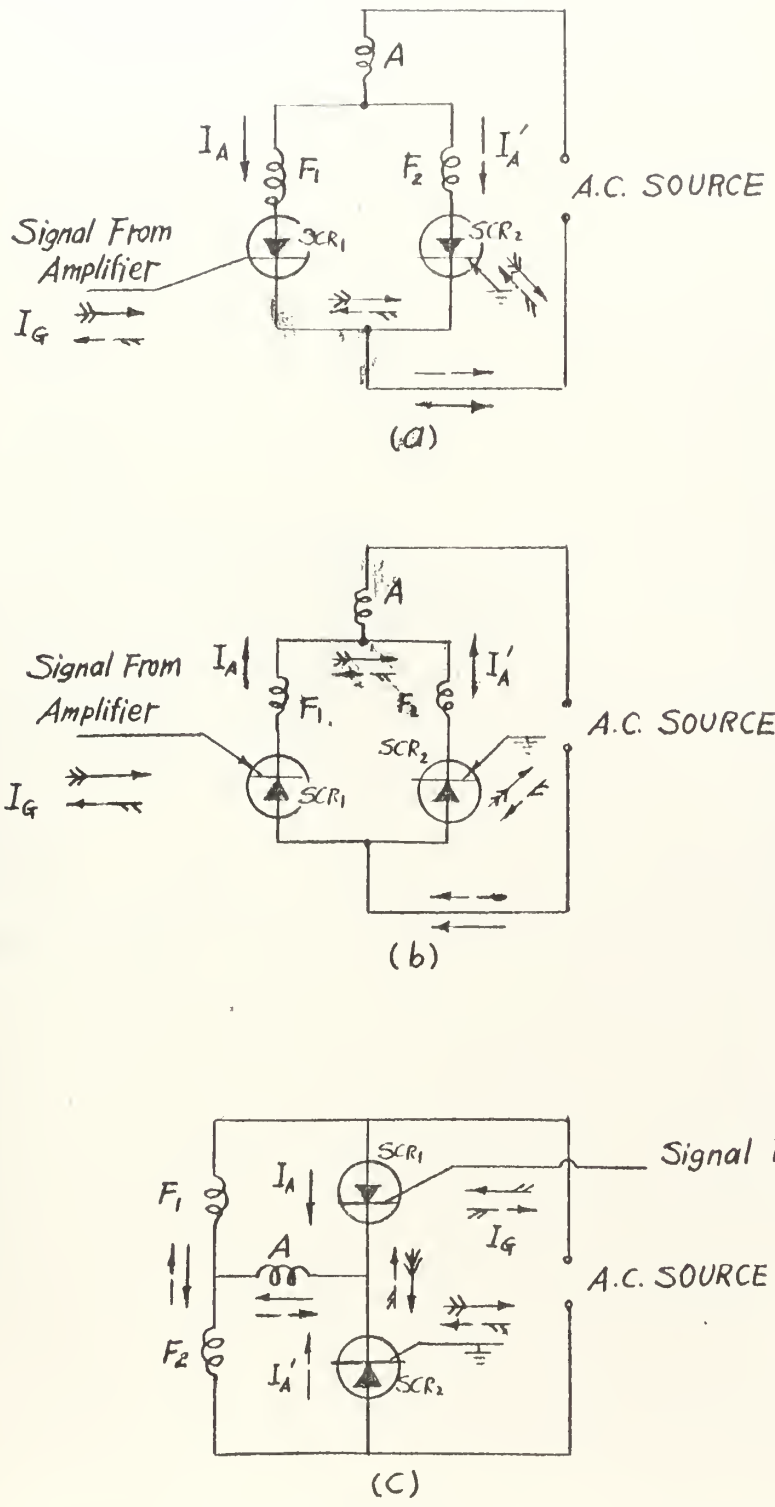


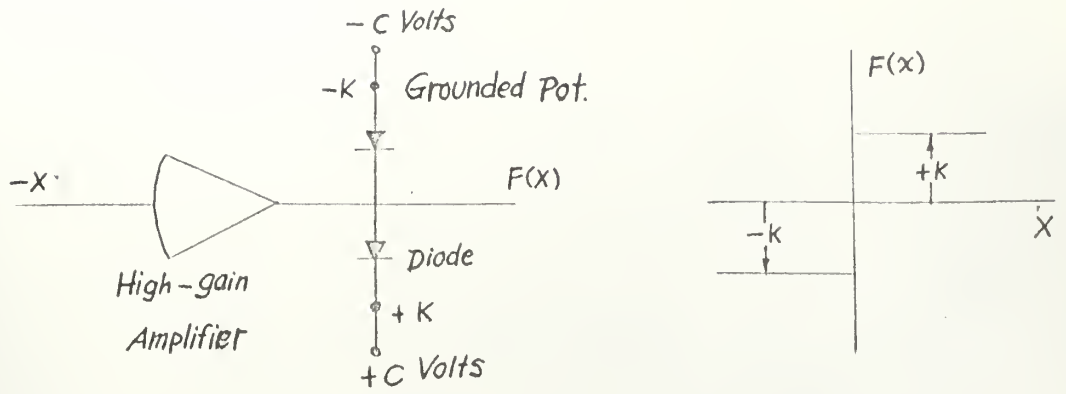
Fig. 4. TRANSISTORIZED RELAY CIRCUITS.

TABLE I

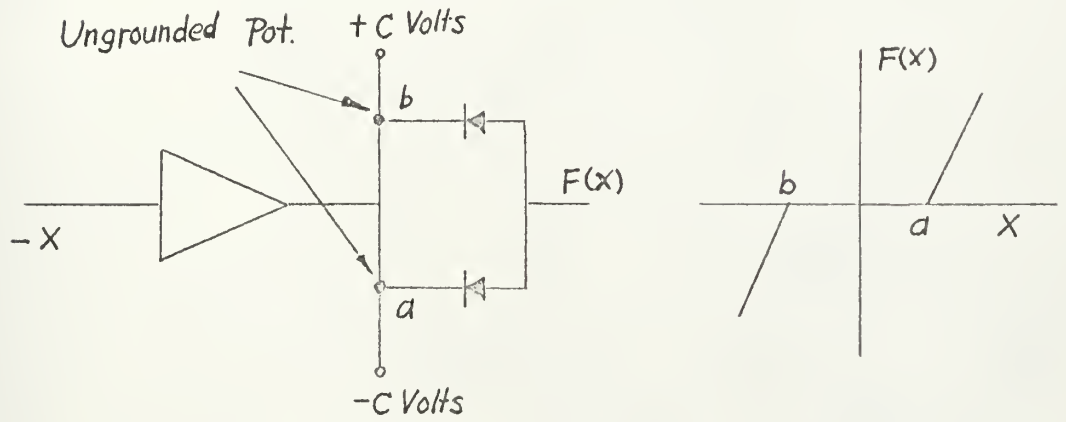
The General Characteristics of Silicon Controlled Rectifier C36A

Continuous Peak Inverse Voltage	100 Volts
Transient Peak Inverse Voltage (Non recurrent 5 millisec)	150 Volts
RMS Voltage, Sinusoidal	70 Volts
Average Forward Current (If)	Up to 10 Amperes
Peak Gate Current	2 Amperes
Peak G te Voltage	10 Volts
Minimum Forward Breakover Voltage	100 Volts
Maximum Reverse or Forward Leakage Current	12.5 ma
Maximum Gate Current to Fire	85 ma
Maximum Gate Voltage to Fire	3.5 Volts
Turn-on time	1.00-4.5 microsec.
Turn-off time	10-20 microse.
Gate current to Fire	8 ma -1.2 Volts.

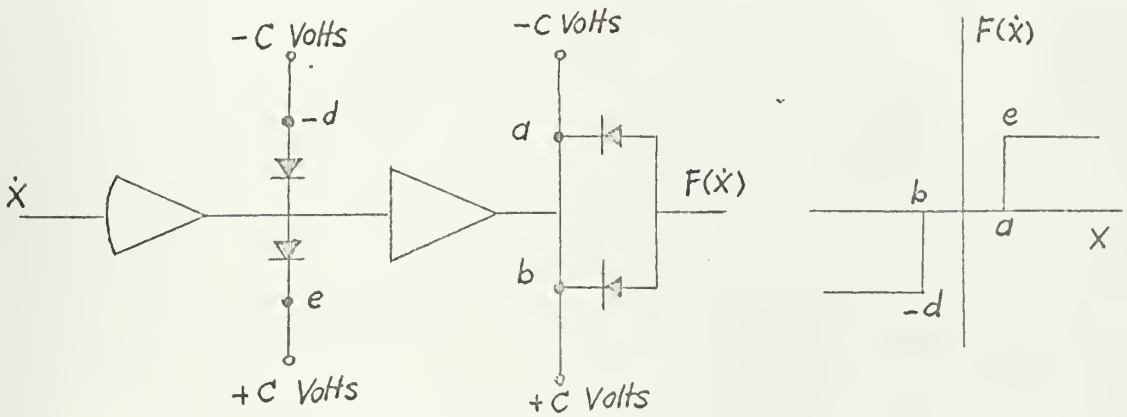
combining the so called "Bang-Bang" circuit and dead zone circuit to form a relay characteristic. The reason for this, adding the dead zone circuit to the "Bang-Bang" circuit, is to eliminate the system hunting motion or limit cycle. The advantage of this method is that the dead zone can be adjusted to required value. However, since it required more amplifiers to operate this combined circuit, this method was not used in this experimental system. The circuit is shown in Fig. 5. The systems techometer is Type FD-36 made by Electric Indicator Co.Inc. It's calibration is shown in Fig. 6. The comparison of transistorized relay and contactor type relay is shown in Fig. 7. The Silicon control rectifier only takes 1.2 volts, gate to cathode voltage, and 8 ma to turn on. However, the contactor type relay, Sigma Model 6FX4C 5000 GD-SIL, takes about 6.1 volts and -6.0 volts to pull in, and 1.2 volts and -1.4 volts to drop out. Thus, the transistorized relay is closerto the ideal relay characteristic.



(a) BANG-BANG CIRCUIT.



(b) DEAD ZONE CIRCUIT.



(c) COMBINING CIRCUIT.

Fig. 5. BANG-BANG, DEAD ZONE, COMBINING CIRCUIT.

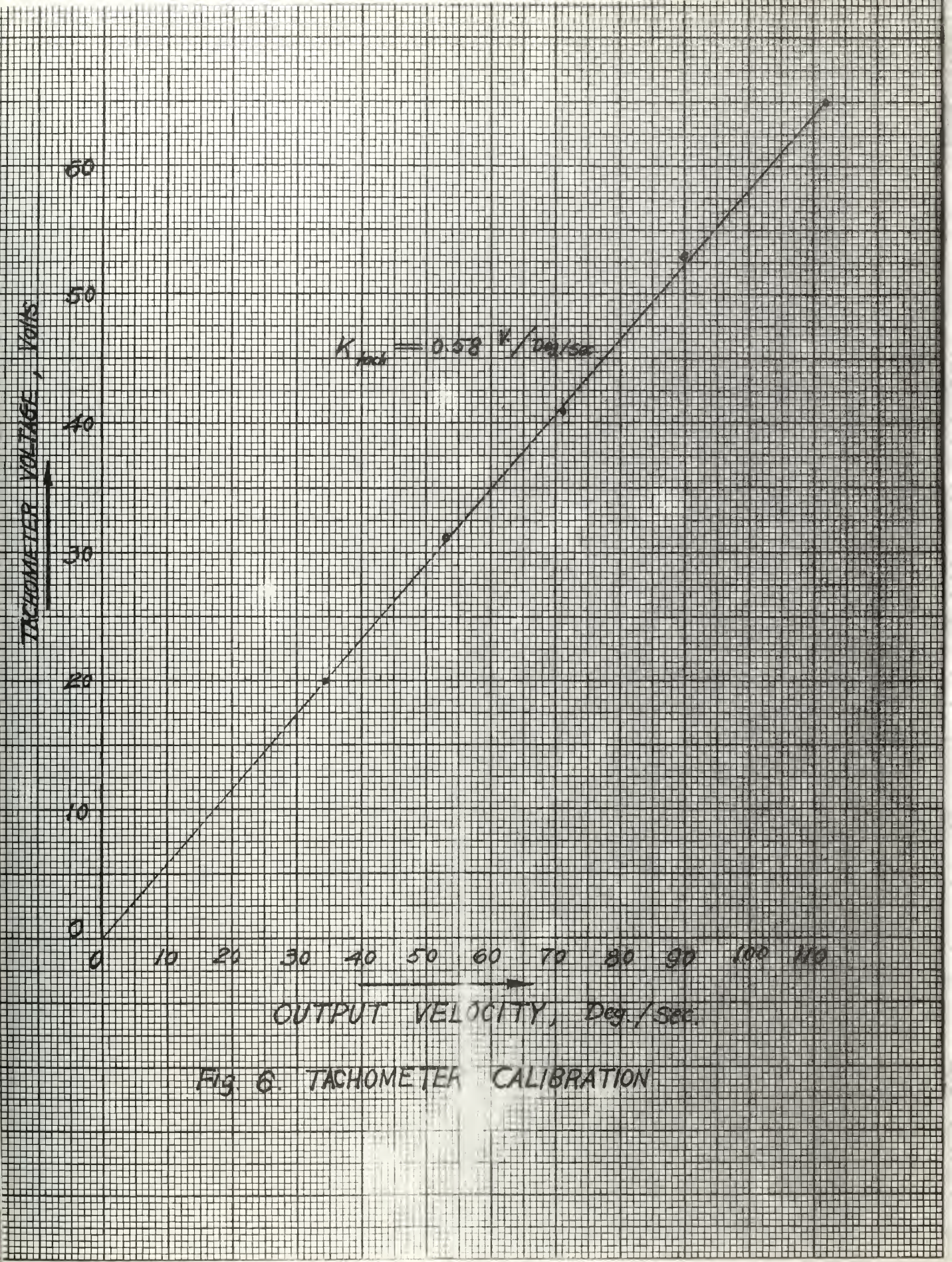


Fig. 6. TACHOMETER CALIBRATION

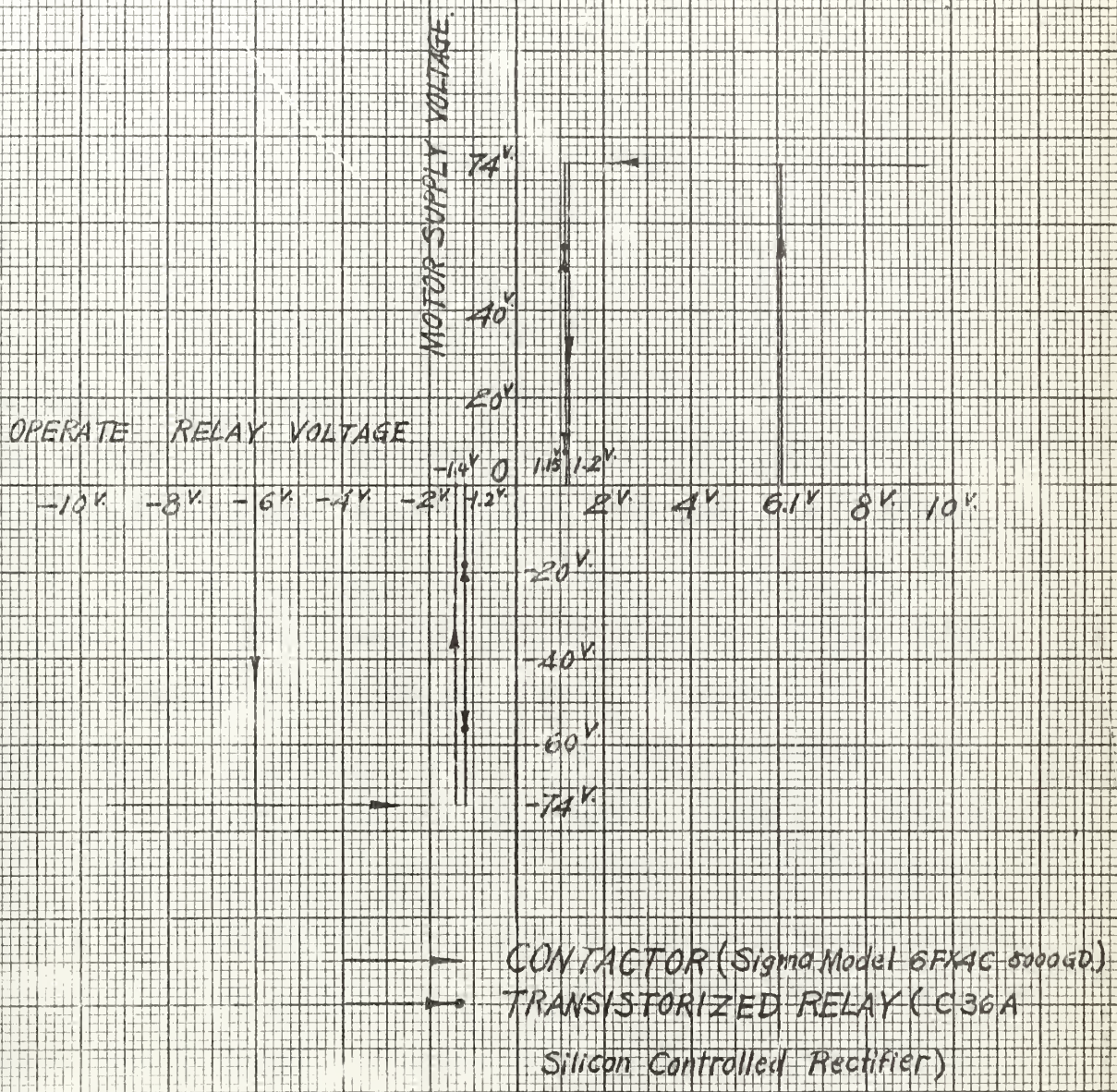


Fig. 7. THE COMPARISON OF TRASISTORIZED RELAY TO CONTACTOR RELAY

3. Filter Design

Since the experimental system is well damped, the proper negative tachometer feedback will get optimum response control. In order to study the effect of filters on poor damped system response, the positive tachometer feedback and different filters are used in the experimental system. Another reason to test filter effect in optimum response control is that the tachometer feedback is not always available in industrial control systems. In addition, the filters are easily constructed, and at low cost. Generally speaking, the ideal relay's switch line is a straight line which divides the phase-plane into two regions, one for positive torque and one for negative torque. The slope of this divided line with ninety degrees in slope passes through the origin. But the slope of the switch line is changed due to the different damping effects. Derivative signal effect, for example, rotates the switch line in counter-clockwise direction to certain angle. In the testing system the negative error rate feedback control had the same effect, and made the system more stable. However, the positive error rate feedback had just the opposite effect, and turned the switch line in clockwise direction and made system more unstable. In the testing system, the limit cycle of finite amplitude is present when the amount of positive error feedback is over the system allowable value.

The filters have about the same effect as derivative signals. The popular filter used in relay servomechanisms is the lead networkfilter. It is shown in the Fig. 1 block diagram, and its physical construction is shown in Fig. 8. Using the mathematical approach, the transfer function of Fig. 8 filter has the following expression:

$$G_f(s) = \frac{s+a}{s+b} = \frac{a}{b}\left(\frac{1+s/a}{1+s/b}\right) = K_f \frac{1+sT_a}{1+sT_b} ,$$

Where gain of the filter

$$K_f = \frac{R_3}{R_1+R_3} ,$$

Time constants

$$T_a = R_1 C_2 , \qquad T_b = \frac{R_1 R_3}{R_1+R_3} C_2 .$$

These results are derived from the following equations:

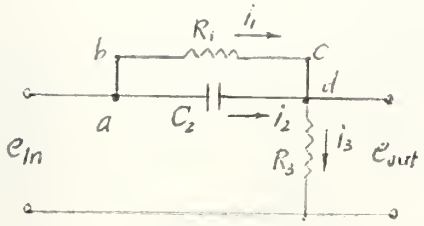


Fig. 8. FILTER.

The transient currents flowed in the different branches of the network are assumed as arrow direction.

$$\bar{e}_{in} = \frac{\bar{i}_2}{C_2 S} + R_3 \bar{i}_3 \qquad \text{in loop abcda}$$

$$\bar{e}_{in} = R_1 \bar{i}_1 + R_3 \bar{i}_3 \qquad \text{in loop ade}$$

$$0 = -\bar{i}_3 + \bar{i}_1 + \bar{i}_2 \qquad \text{at node d.}$$

By using determinant method solve i_3 from about three equations,

we get:

$$\bar{i}_3 = \frac{\begin{vmatrix} 0 & \frac{1}{C_2 S} & \bar{e}_{in} \\ R_1 & 0 & \bar{e}_{in} \\ 1 & 1 & 0 \end{vmatrix}}{\begin{vmatrix} 0 & \frac{1}{C_2 S} & R_3 \\ R_1 & 0 & R_3 \\ 1 & 1 & -1 \end{vmatrix}}$$

$$= \frac{\frac{\bar{e}_{in}}{C_2 S} + \bar{e}_{in} R_1}{\frac{R_3}{C_2 S} + \frac{R_1}{C_2 S} + R_1 R_3}$$

But $\bar{e}_{out} = R_3 \bar{i}_3$,

$$\text{So} \quad \bar{e}_{out} = R_3 \frac{\frac{\bar{e}_{in}}{C_2 S} + \bar{e}_{in} R_1}{\frac{R_3}{C_2 S} + \frac{R_1}{C_2 S} + R_3 R_1}$$

This rearranges to:

$$\frac{\bar{e}_{out}}{\bar{e}_{in}} = \frac{R_3 (1 + C_2 R_1 S)}{(R_3 + R_1)(1 + \frac{C_2 R_1 R_3}{R_1 + R_3} S)}$$

So we get the final result:

$$\frac{\bar{e}_{out}}{\bar{e}_{in}} = K_f \frac{1 + S T_a}{1 + S T_b}$$

Since the silicon controlled rectifier has very short time delay up to 1.5 microsec, its transfer function can be assumed, no time delay and only high power gain. The transfer function of the whole transistorized controller enclosed filter relay and amplifier, is as

$$G_c = K \frac{1 + S T_a}{1 + S T_b}$$

Where K is the total gain of controller.

Expanding denominator in a power series:

$$\frac{1}{1 + S T_b} = 1 - S T_b + S^2 T_b^2 - S^3 T_b^3 + \text{----}$$

Investigating the above power series, if T_b is very small, the power series can be reduced in a short form without introducing large error.

That is:

$$\frac{1}{1 + S T_b} = 1 - S T_b$$

So G_c can be rewritten as:

$$G_c = K(1+ST_a)(1-ST_b)$$

$$= K(1+ST_a-ST_b+S^2T_aT_b)$$

If T_a is a small number less than one, we can neglect the fourth term, $S^2T_aT_b$, without introducing large error in shifting the divided line. So final approximate result is:

$$Gc = K(1+ST_a-ST_b)$$

$$or\ Q(t) \doteq KE(t)+K(T_a-T_b)\dot{E}(t)$$

Where signal Q (t) actually operates the transistorized relay and causes it to supply full power to motor and to load. The power supply to motor reverses when Q(t) goes through zero.

So when we put Q(t)=0,

we get:

$$KE\ (t)+K(T_a-T_b)\dot{E}(t)=0$$

$$\frac{\dot{E}(t)}{E(t)} = \frac{-1}{T_a-T_b}$$

So the shifting angle between divide line and E axis is

$$\phi = tan^{-1}|T_a-T_b|$$

When $T_a > T_b$, the divided line will rotate to counterclockwise direction. The negative slope of this divided line will make system more stable. On the other hand, when $T_a < T_b$, the switch line will rotate to clockwise direction, make system unstable.

As shown in the previous expression, the time constant of filters T_a and T_b are dependent upon the adjustable resistance of R_1, R_3, and capacitance C_2. After properly adjusting these filter elements, the

system can get very nice optimum response.

The experiment results agree with the above mathematical analysis. The same kind of filters but with different elements of resistance and capacitance have been used in the experimental system. The results are shown in Fig. 35 to Fig. 61. More detailed discussions will be presented later.

According to the approximate calculation, the different switch line rotating angles are listed on the following table.

TABLE II.

The effect of lead network on relay switch line

Filter No.	R_1K	R_3K	C_2 uf	T_a	T_b	$T_\varepsilon - T_b$	0
1	500	100	1	0.5	0.0833	0.4167	22°37'
2	500	100	2	1.0	0.1667	0.8330	39°48'
3	500	50	2	1.0	0.0909	0.9091	42°17'
4	500	25	2	1.0	0.0476	0.9524	43°36'
5	200	100	1	0.2	0.0667	0.0133	7°36'
6	95	10	1	0.095	0.00905	0.08595	4°55'
7	45	10	1	0.045	0.00818	0.03682	2° 6'

4. Transient and Frequency Response of Natural System with Position Error Feedback Control for Step Input.

Fig. 9 and Fig. 10 shows the transient response of the experimental system with position error feedback control only. It's block diagram is shown previously in Fig. 1(a). The natural system is well damped, so the output θc does not take more than two osciallations. Its peak overshoot is about twenty percent of step input. The settling times depending upon different input vary from 5.5 seconds for 12.5° to 12 seconds for 62.5 degree displacement input.

The maximum response speed of motor or the peak error rate vary depending upon the step input. It is 7.9 deg./sec. for 12.5° input and 18 deg./sec. for 62.5° input.

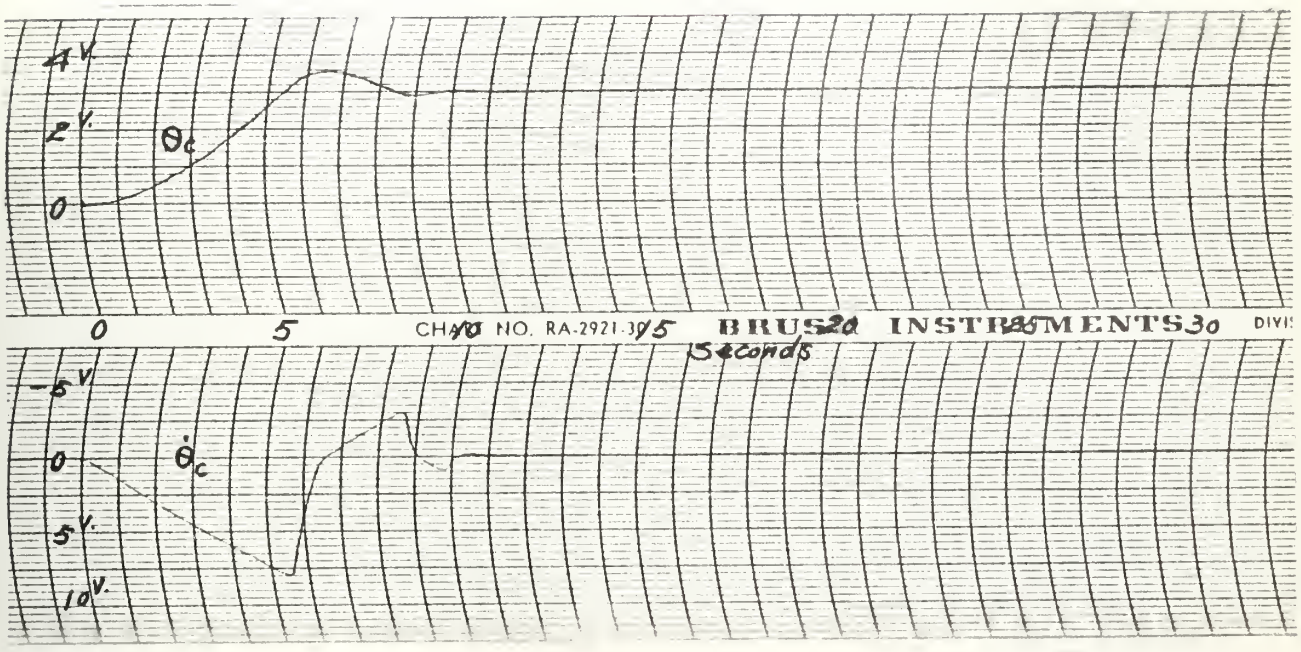
The phase plane trajectories of the natural system with large step input is shown in Fig. 11. The divided line is very close to a straight line which passes through the origin. It almost coincides with Y axis with no dead zone. This means that the silicon controlled rectifier has a better characteristic than the general contactor type relay with some dead zone and different pull-in and drop-out voltage requirements. There is also negligible time delay.

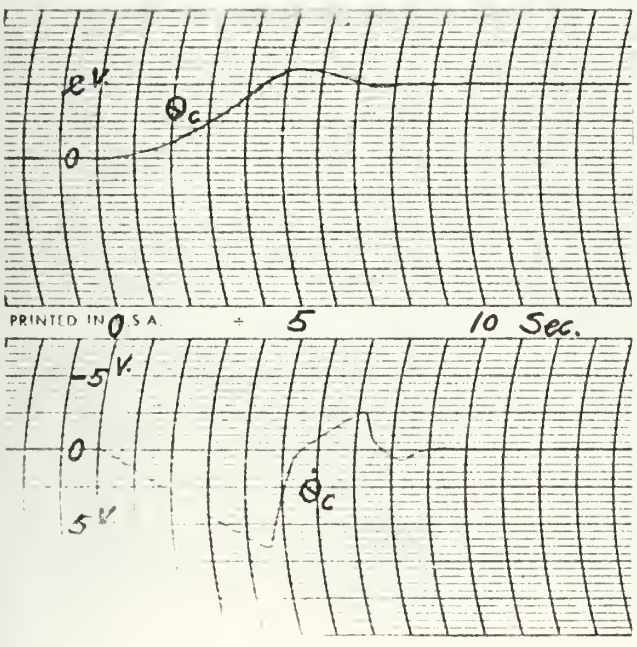
Fig. 12 and Fig. 13 shows the natural system transient response for small step-displacement input. It is still kept under twenty percent overshoot, but settling time is shorter than large step-displacement input. Their phase plane trajectories are shown in Fig. 14. It is shown flat top on 0.25 volts step-displacement input in phase plane. This perhaps shows the dead zone of the silicon controlled rectifier. It can be decreased if system amplifier gain can be increased.

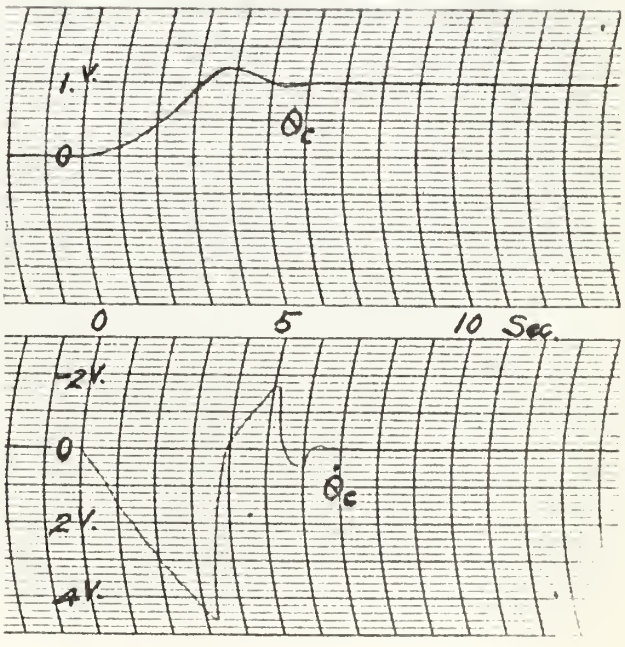
The frequency response curve of natural system with 4 volts and 8 volts peak-to-peak sinusoidal input are shown in Fig. 15 and Fig. 16.

Comparing the two magnitude vs. frequency curves in Fig. 15, we get the expected results, namely the transient and frequency response agreement. Since the large step-displacement input has a longer average period of oscillation than the small step-displacement input, the frequency of transient response is lower by definition of their relationship. In linear servomechanisms the higher resonance frequency occurs when it is the higher transient oscillating frequency. It is also true when it is applied to nonlinear servomechanisms like this experimental system. The 8 volts step-displacement input has a longer period of oscillation than the 4 volts step input, therefore its resonance frequency is 0.04 CPS lower than 4 volts step input resonance frequency 0.053 CPS.

Fig. 16 shows the phase relation of input and output for 8 volts and 4 volts peak to peak sinusoidal input the faster phase shifting when the frequency is increased.

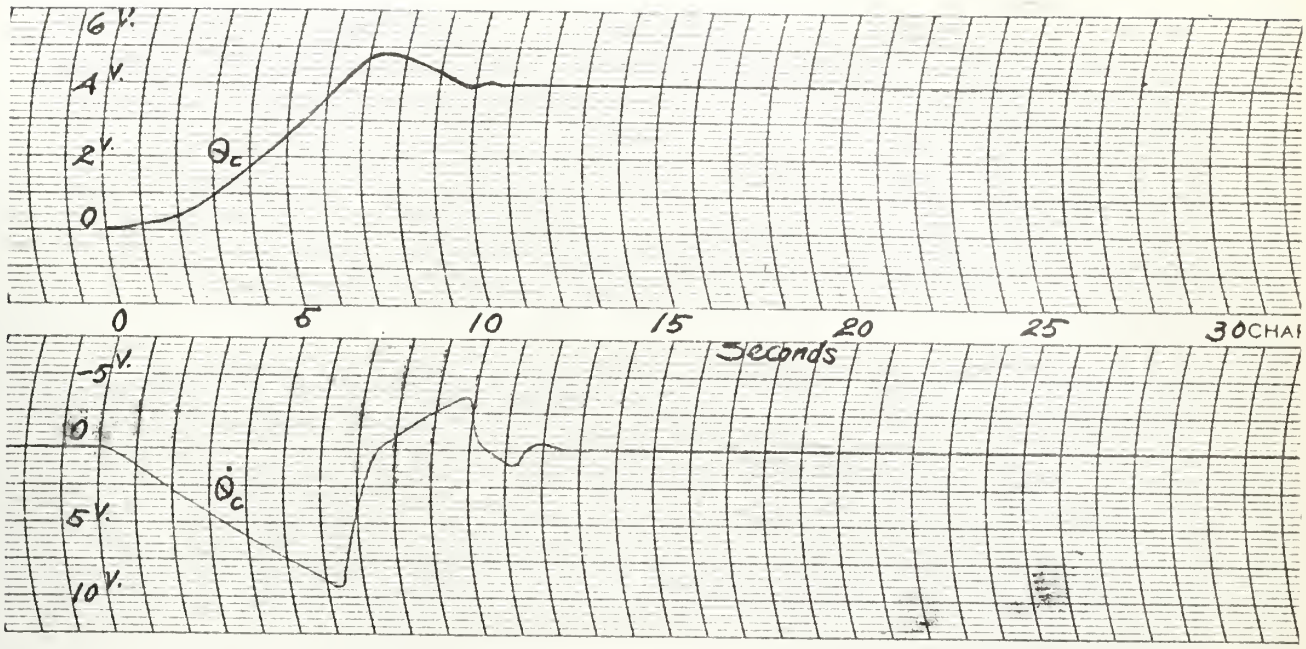






TRANSIENT RESPONSE OF SYSTEM WITH

FEEDBACK FOR LARGE INPUT (1)



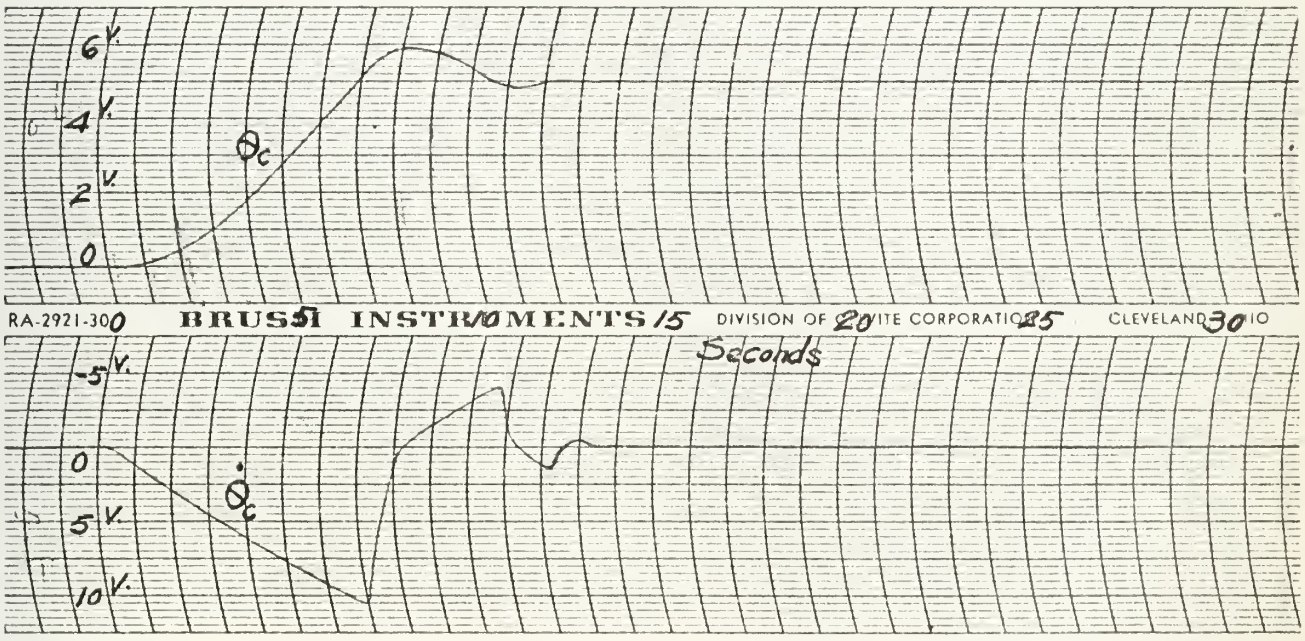


Fig. 10 TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR FEEDBACK FOR LARGE INPUT (2)

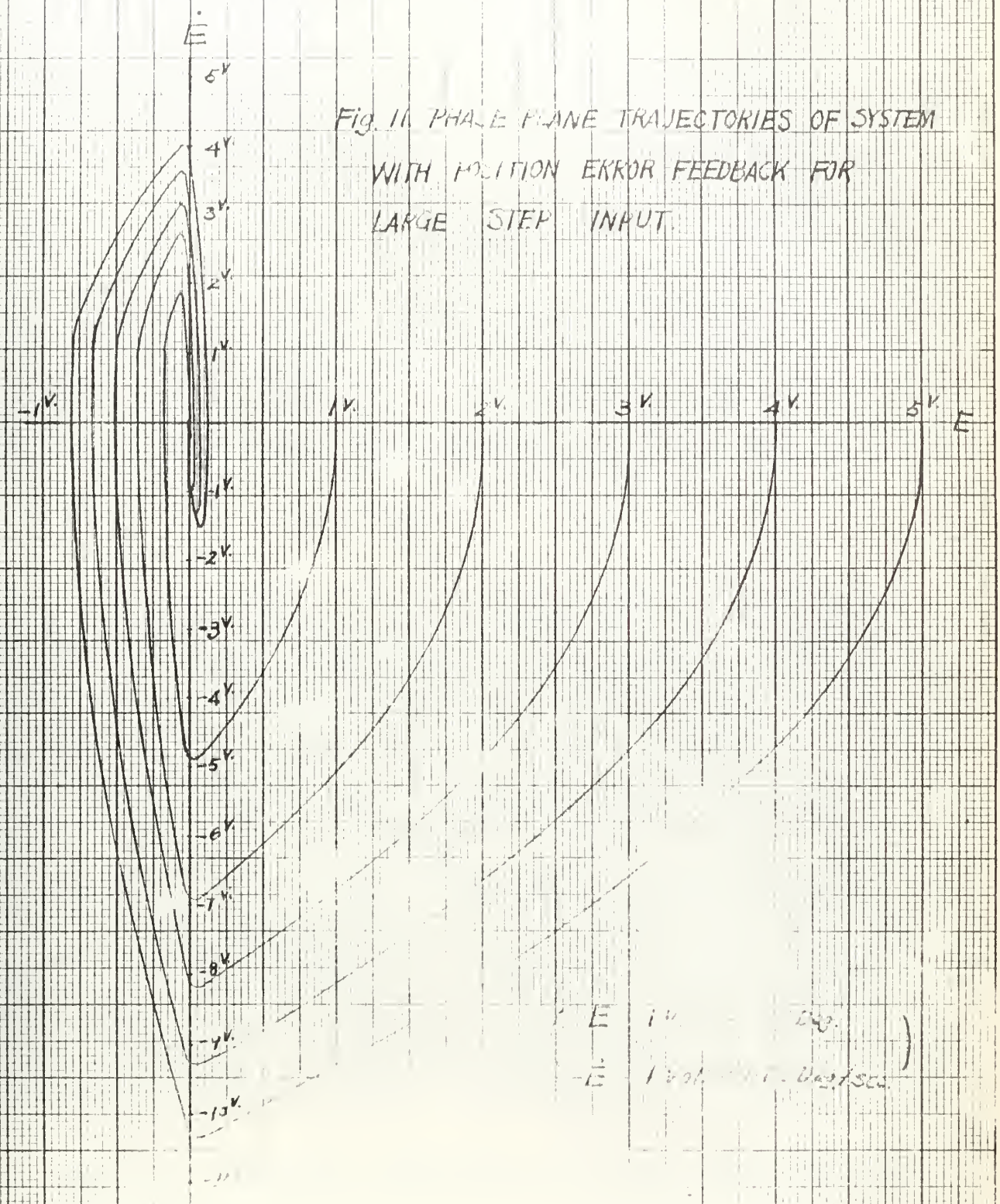


Fig. 11 PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR FEEDBACK FOR LARGE STEP INPUT

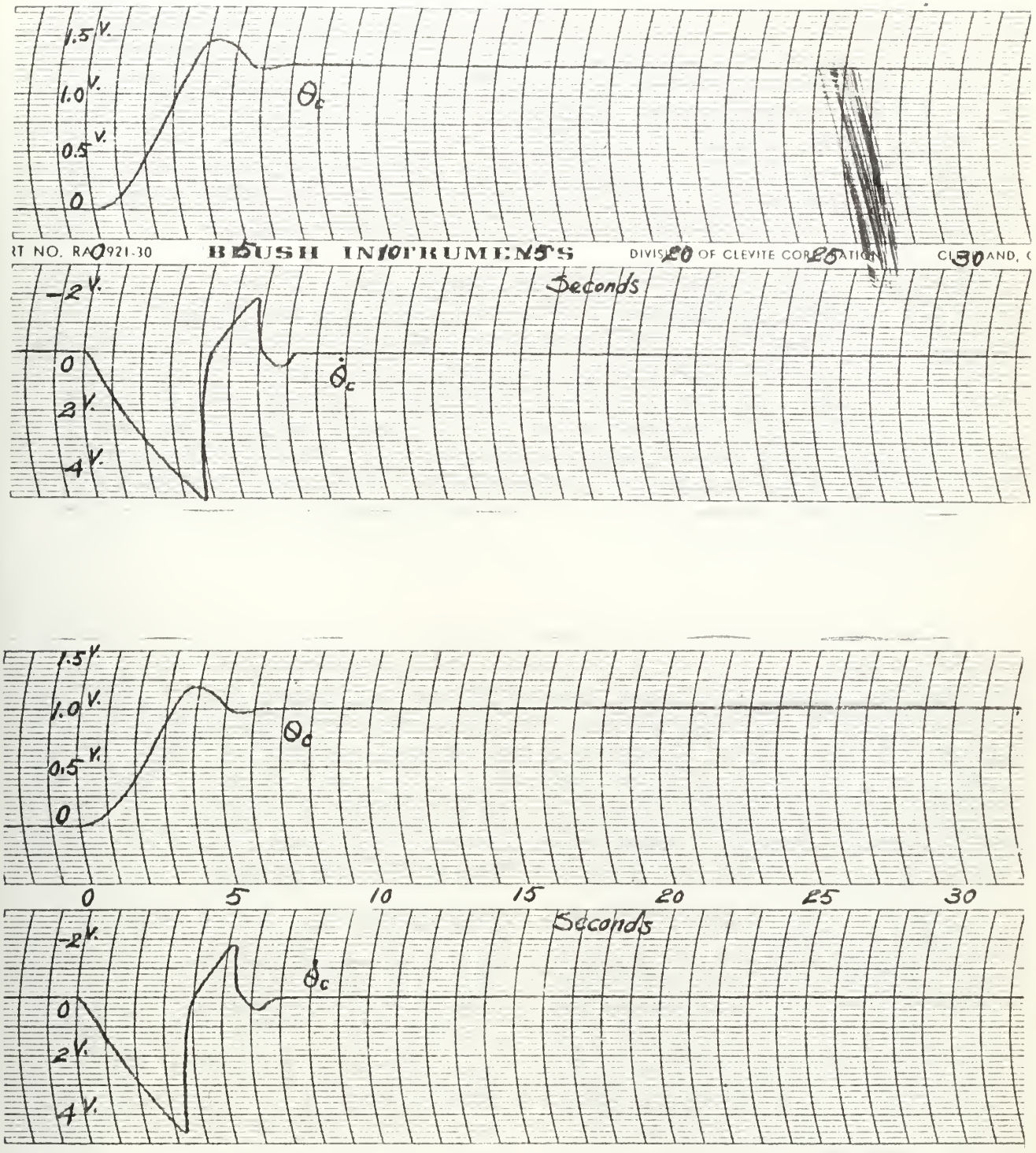
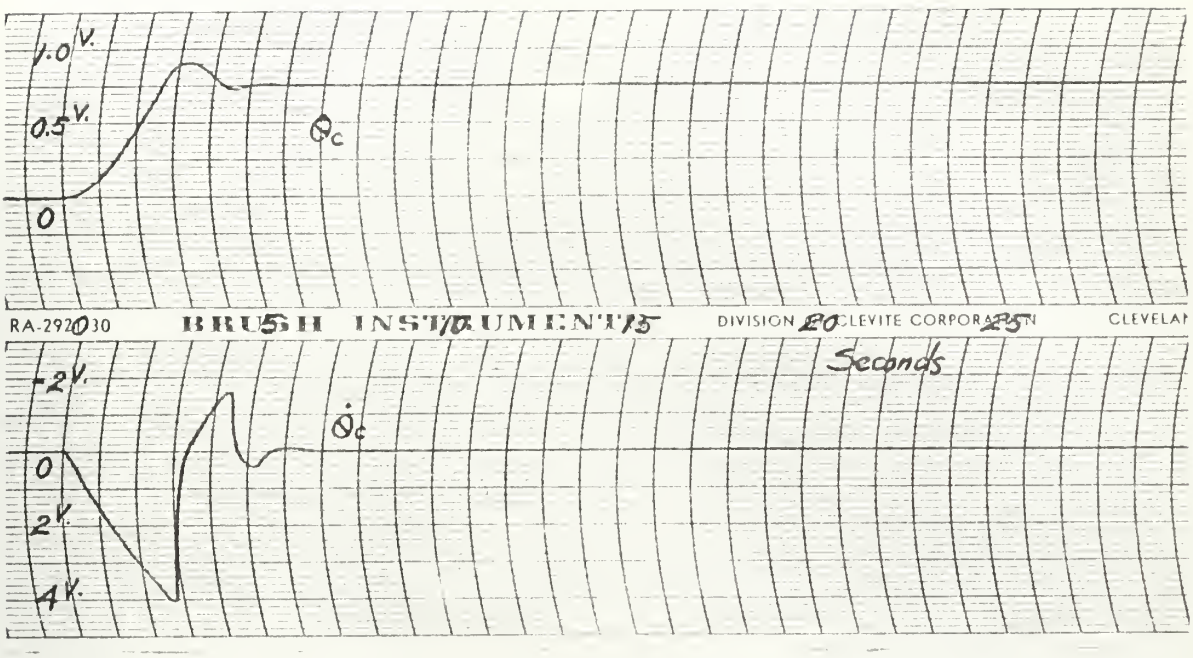


Fig. 12 TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR FEEDBACK FOR SMALL STEP INPUTS (1)



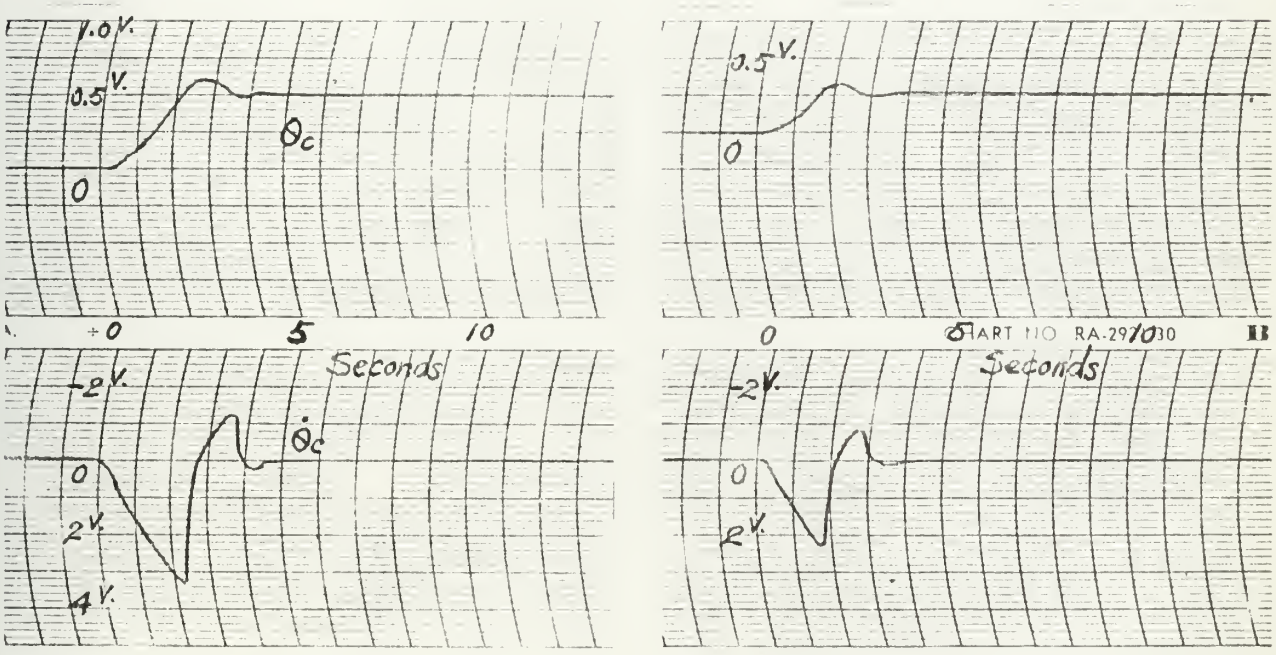


FIG. 13 TRANSIENT RESPONSES OF SYSTEM WITH POSITION ERROR FEEDBACK FOR SMALL INPUT (2)

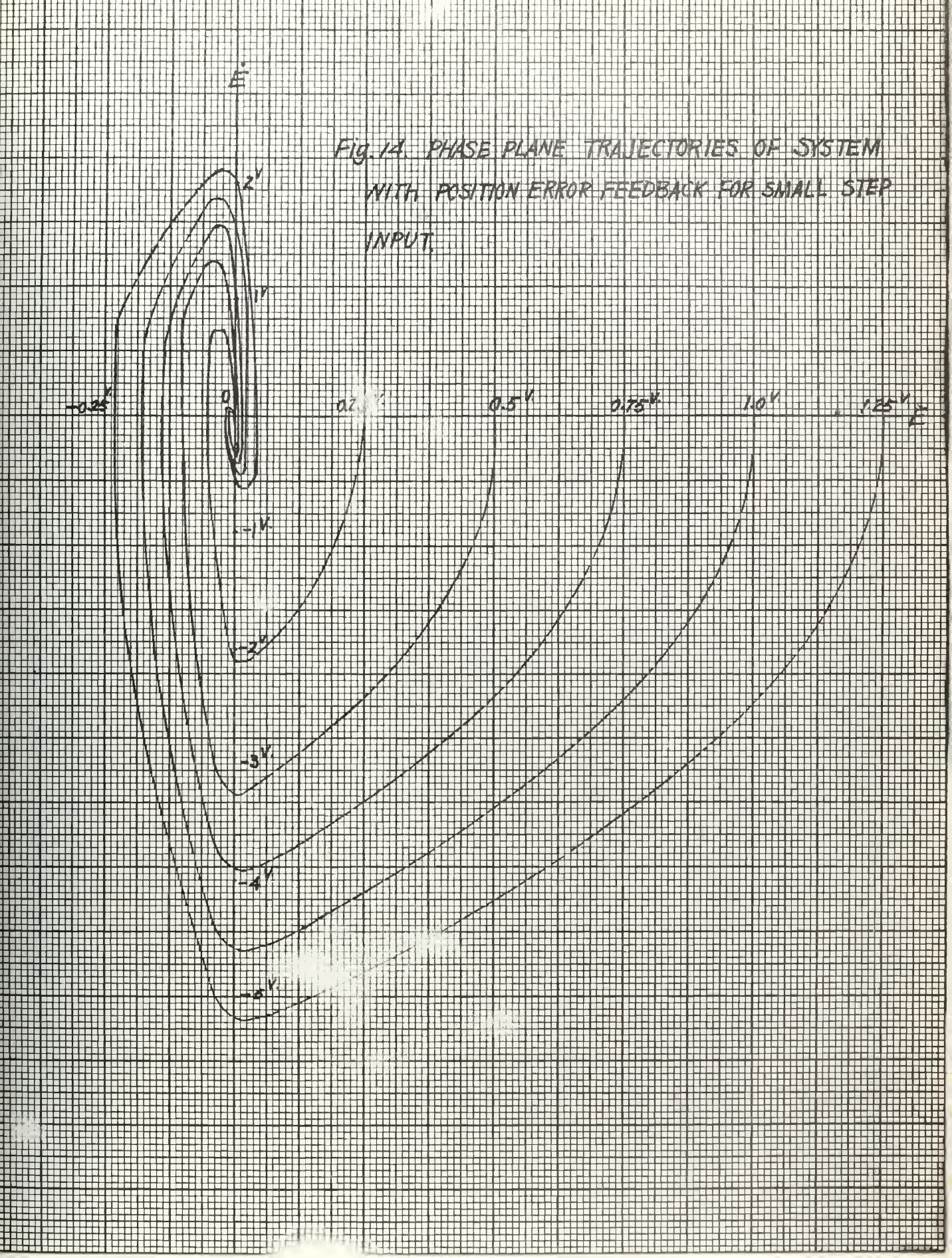


Fig. 14. PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR FEEDBACK FOR SMALL STEP INPUT.

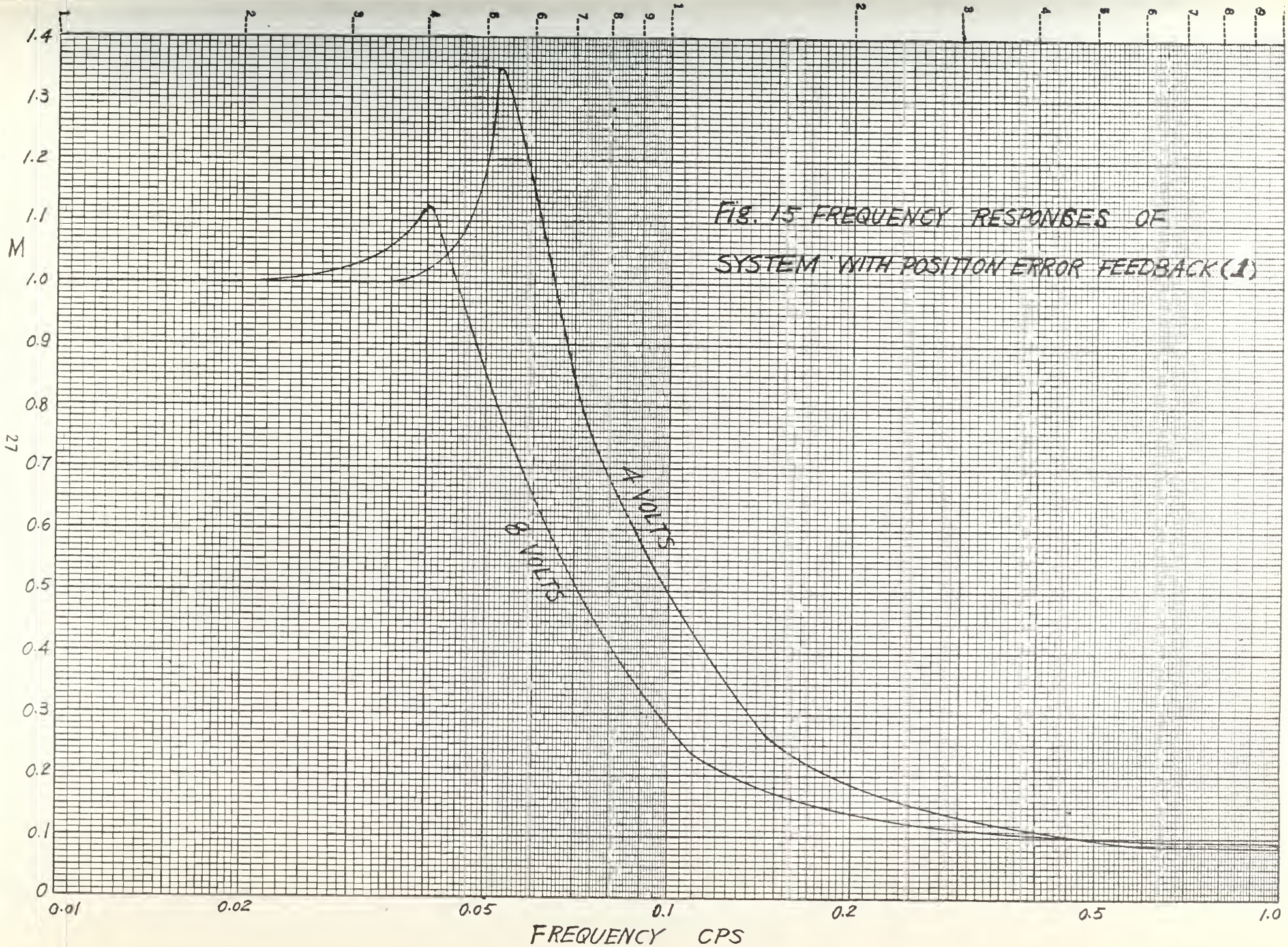


FIG. 15 FREQUENCY RESPONSES OF SYSTEM WITH POSITION ERROR FEEDBACK (1)

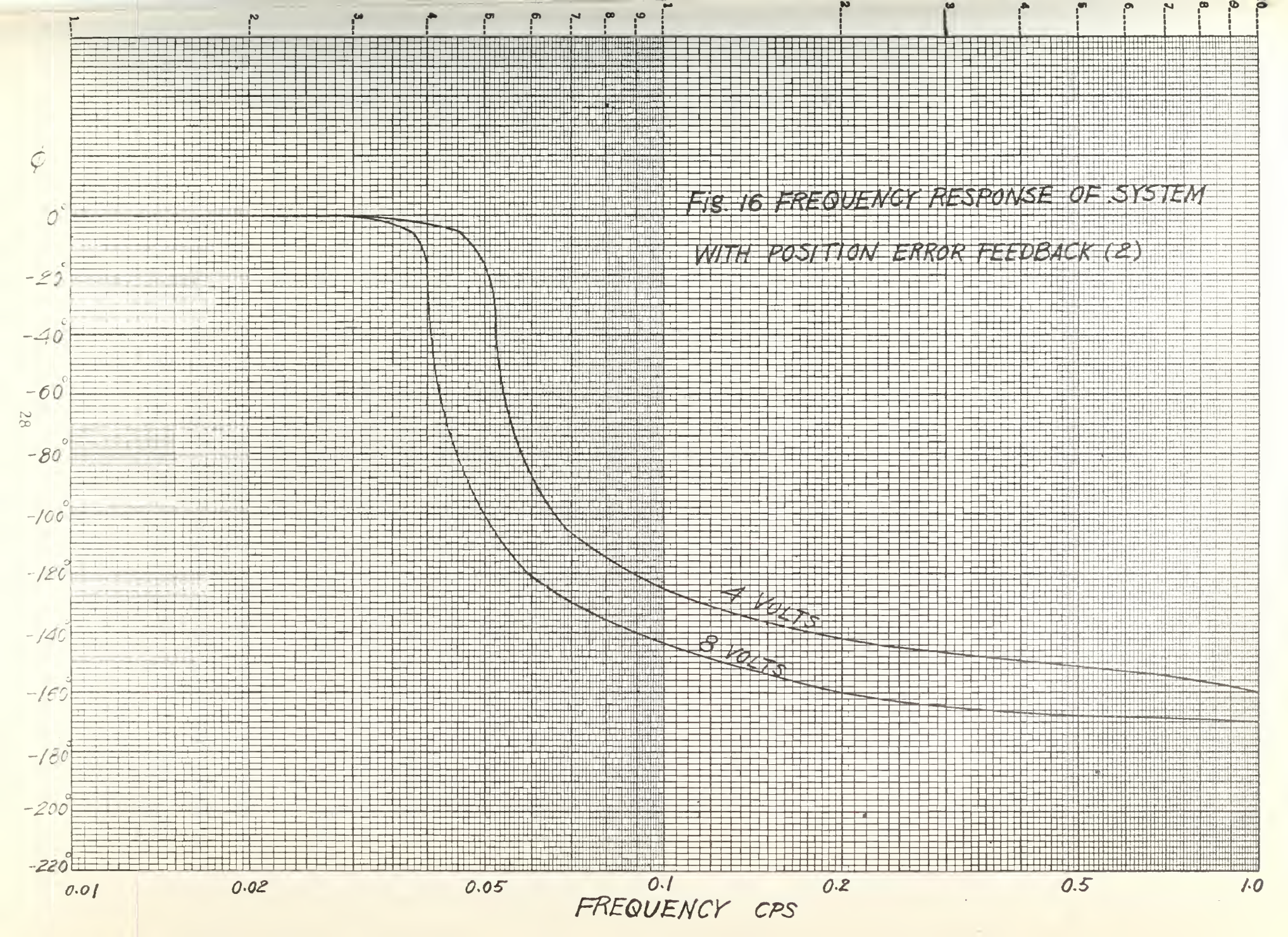


Fig. 16 FREQUENCY RESPONSE OF SYSTEM
WITH POSITION ERROR FEEDBACK (2)
φ
0°
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
-200°
-220°
4 VOLTS
8 VOLTS
0.01
0.02
0.05
0.1
0.2
0.5
1.0
FREQUENCY CPS

5. Transient and Frequency Response of Natural System with Position Error and Negative Error Rate Feedback Control.

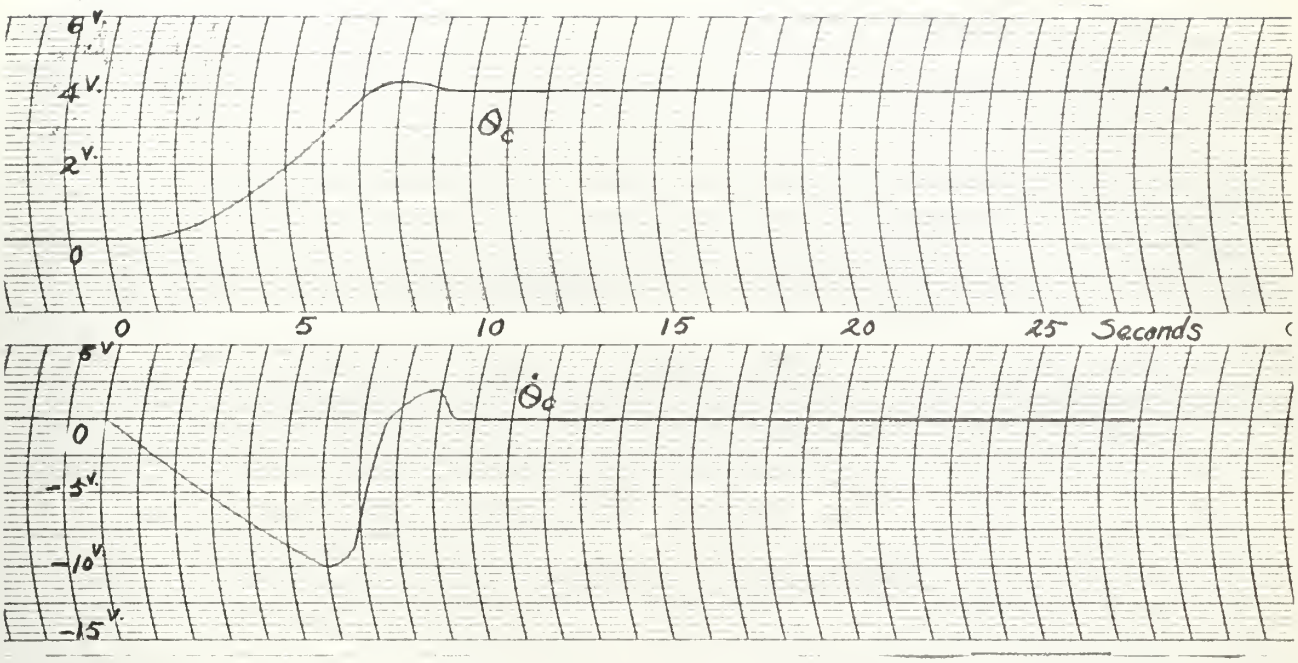
The negative error rate feedback has good effect on system stability, since this feedback shifts the switch line in counterclockwise direction, and makes the experimental system more stable. Many values of negative error rate feedback coefficient h have been tested in the experimental system. The three typical results are shown in Fig. 17 to Fig. 26. By properly adjusting to get the critical value of h, it not only makes the system more stable but also creates the fastest response. The first typical results are shown in Fig. 17 and Fig. 18 for transient response. Their phase-plane trajectories are plotted in Fig. 19. These results have less overshoot and shorter settling time compared to the natural system with position error feedback control. However, this typical result with h equal 0.01667 is still not ideal nor the fastest response since it does not shift the switch line angle enough to eliminate the system overshoot. The shifted angle is about seven degrees.

The second typical results of transient response are shown in Fig. 20 and Fig. 21. They took the longest time in response as compared to the other two typical results. The large error rate feedback shifts the switch line 38 degrees over the optimum response position so that the chattering phenomenon makes the system very slow in response. Especially for small step inputs, the chattering phenomenon is obvious in the region around origin. Their phase-plane plots are shown in Fig. 22. Their negative error rate feedback coefficient h is 0.611.

The third typical results of the error and negative error rate feedback control are shown in Fig. 23 and Fig. 24. This set of transient response curves has the shortest settling times as compared to the other two results.

There is no overshoot and no oscillation. Such a typical result reaches the ideal or optimum response. For the same step displacement input, 8 volts, the settling time in this type of feedback is only 8 seconds. It is 4 seconds shorter than the natural system for error feedback. The error rate feedback coefficient h is 0.161. The switch line is shifting about 17 degrees. The phase-plane trajectories of these typical results are shown in Fig. 25.

The frequency responses of these three different h feedback controls are shown in Fig. 26. The solid line represents the under-damped case. It has the highest resonance peak between the three curves. The broken line shows the critically damped condition. It has resonable resonance peak and fastest response. The broken and dotted line shows the overdamped case. It has no overshoot in transient and frequency response, and is slowest in response.



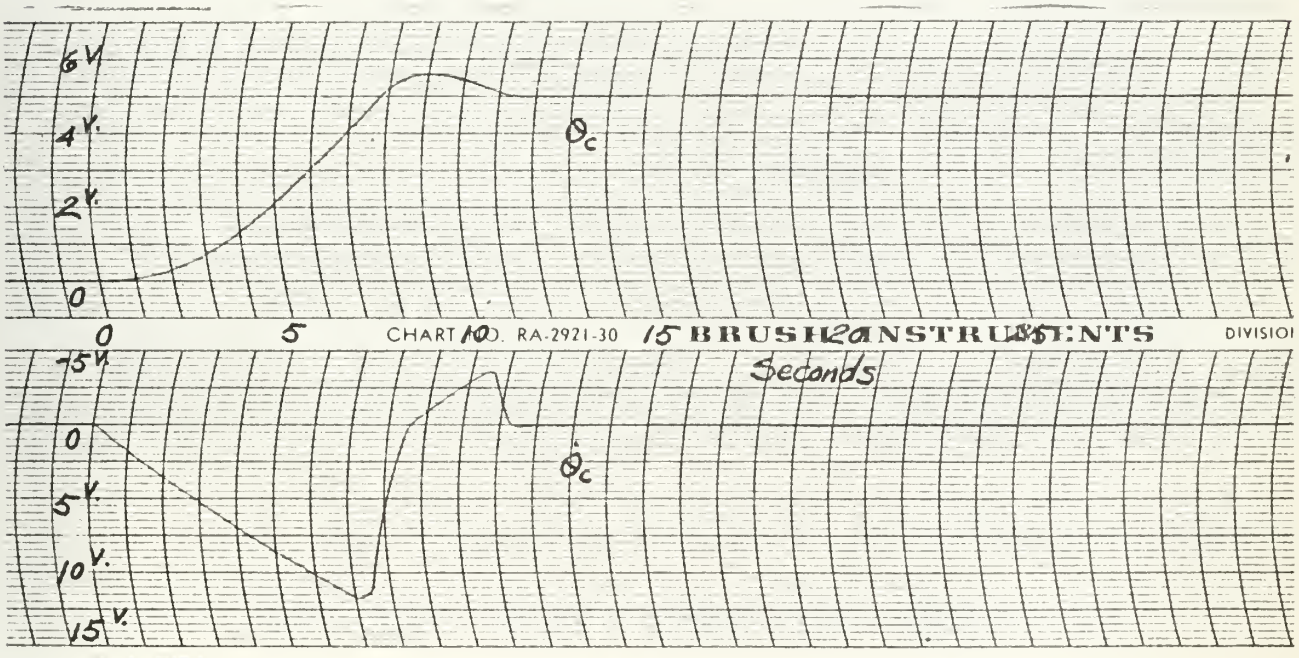
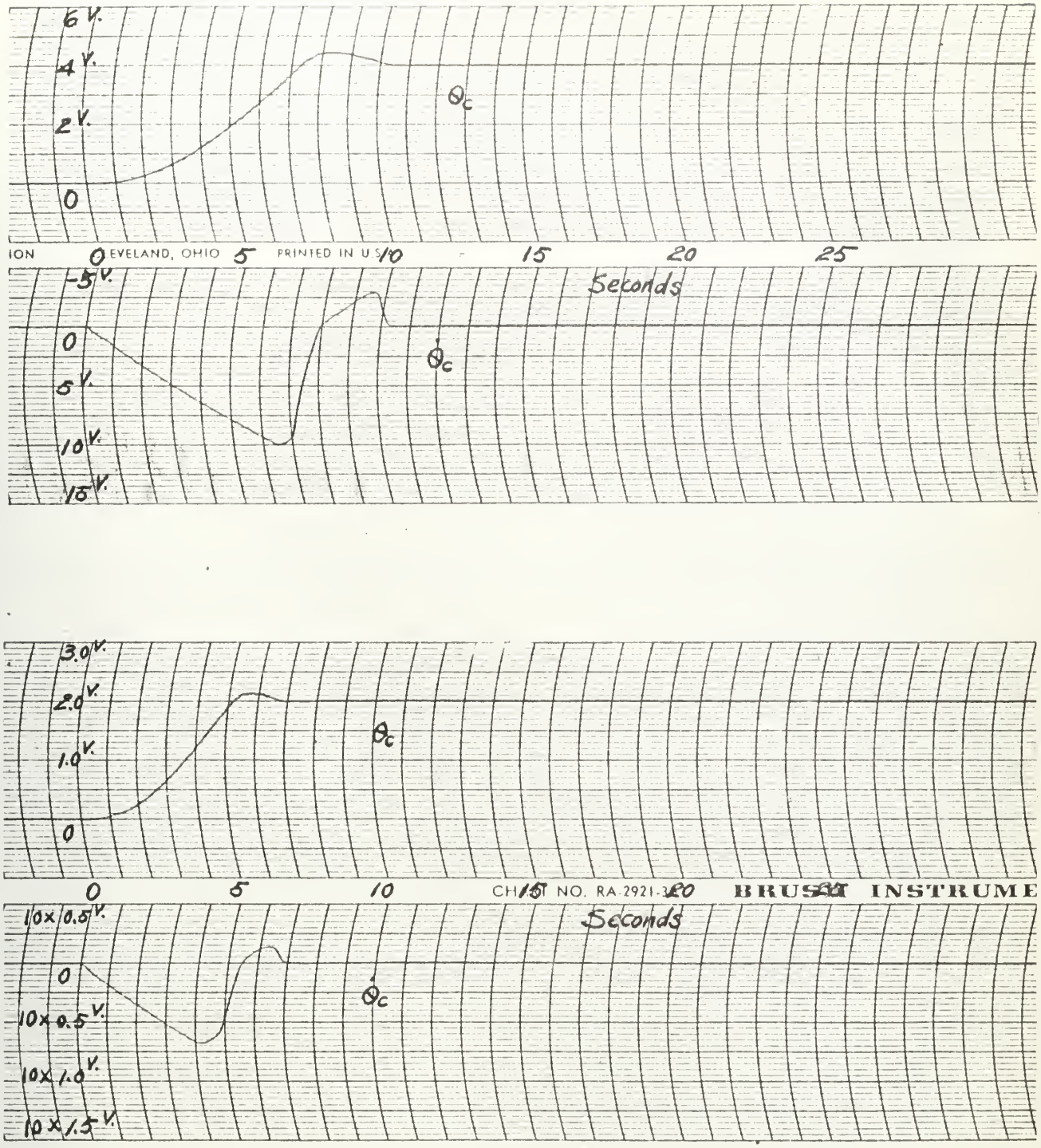


Fig. 17 TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND −0.01667 ERROR RATE FEEDBACK (1)



EVELAND, OHIO PRINTED IN U.S.
CH NO. RA-2921-
BRUSH INSTRUME

Fig. 18 TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND −0.01667 ERROR RATE FEEDBACK (2)

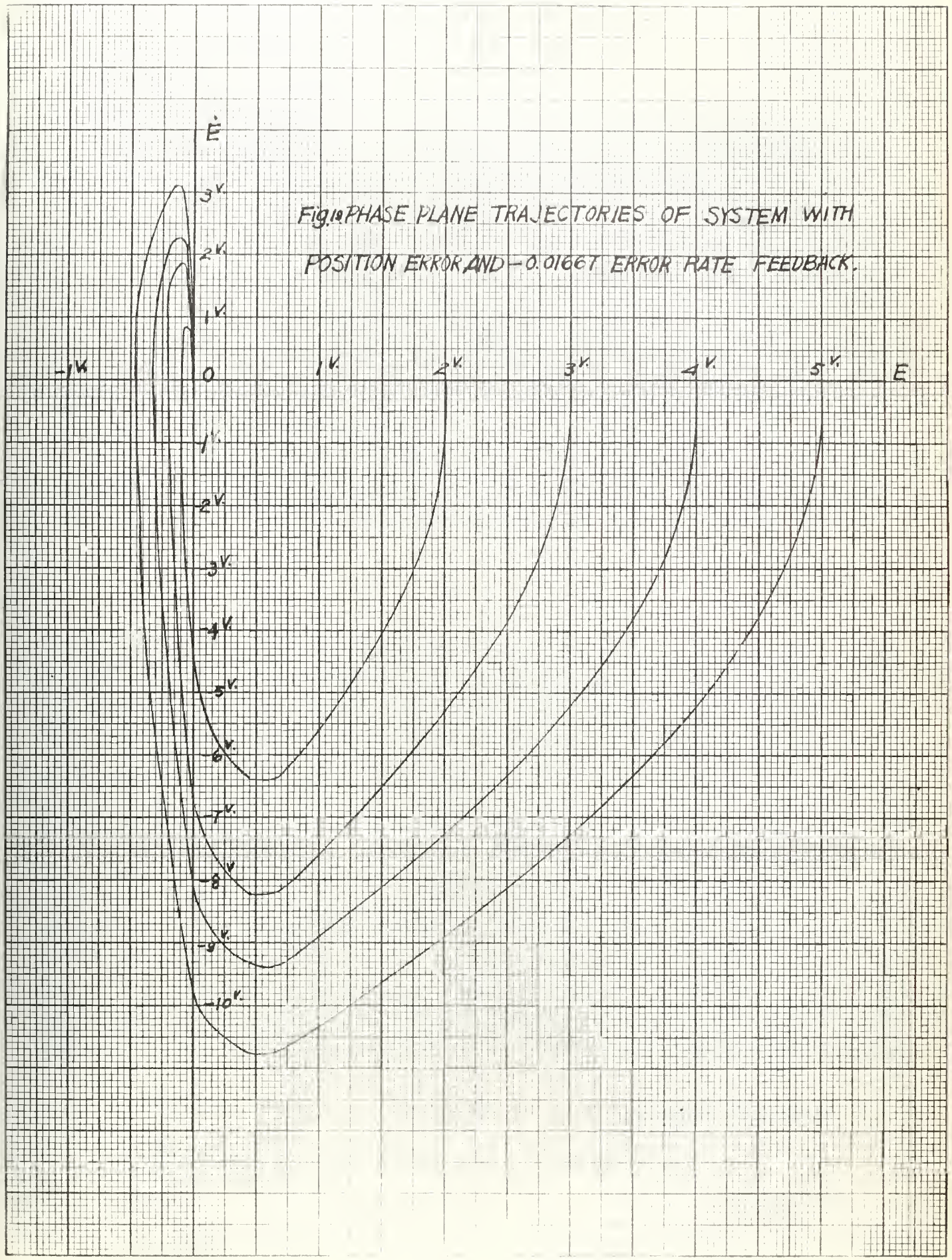


Fig. 10 PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR AND −0.0166T ERROR RATE FEEDBACK.

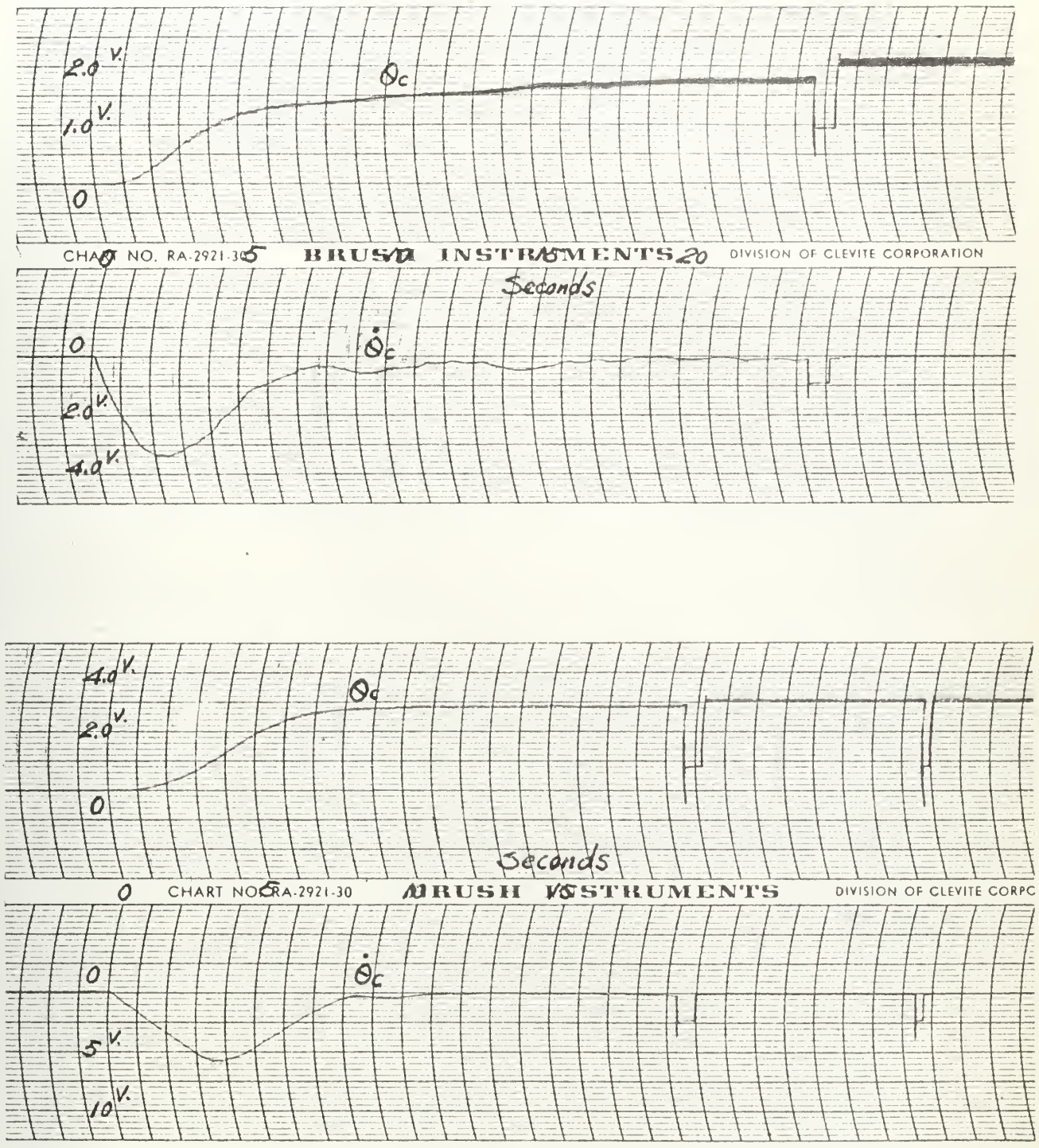
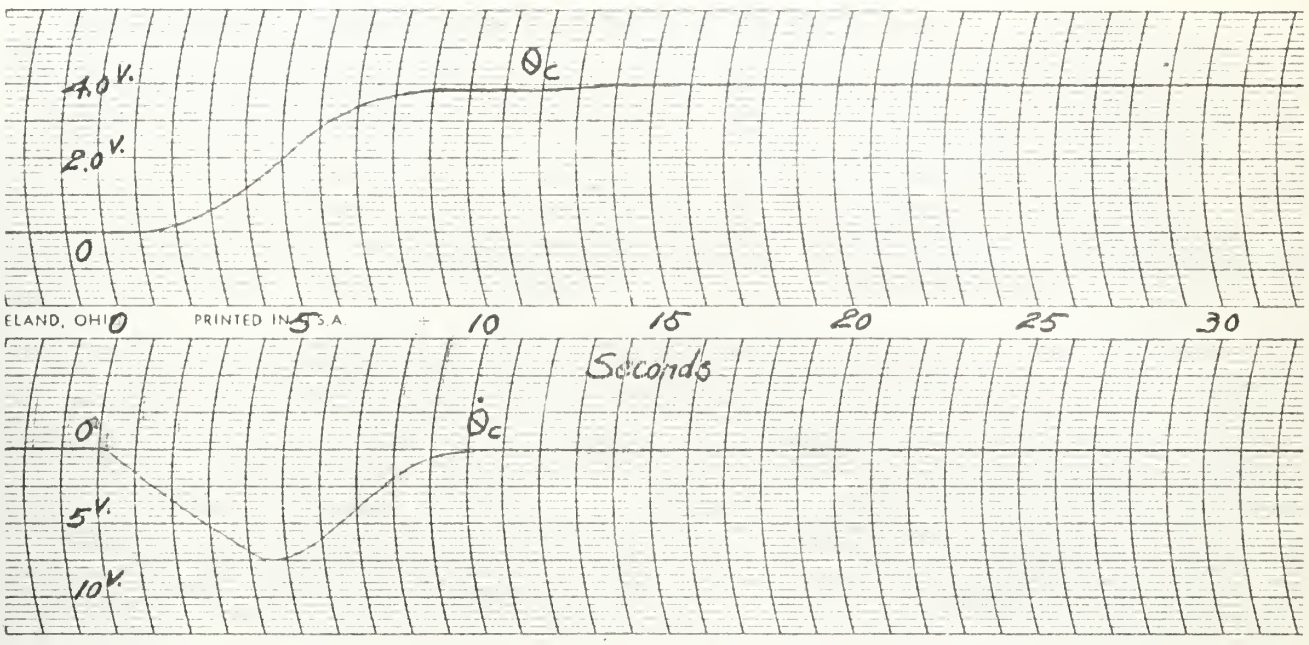


Fig. 20. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND −0.611 ERROR RATE FEEDBACK (1)



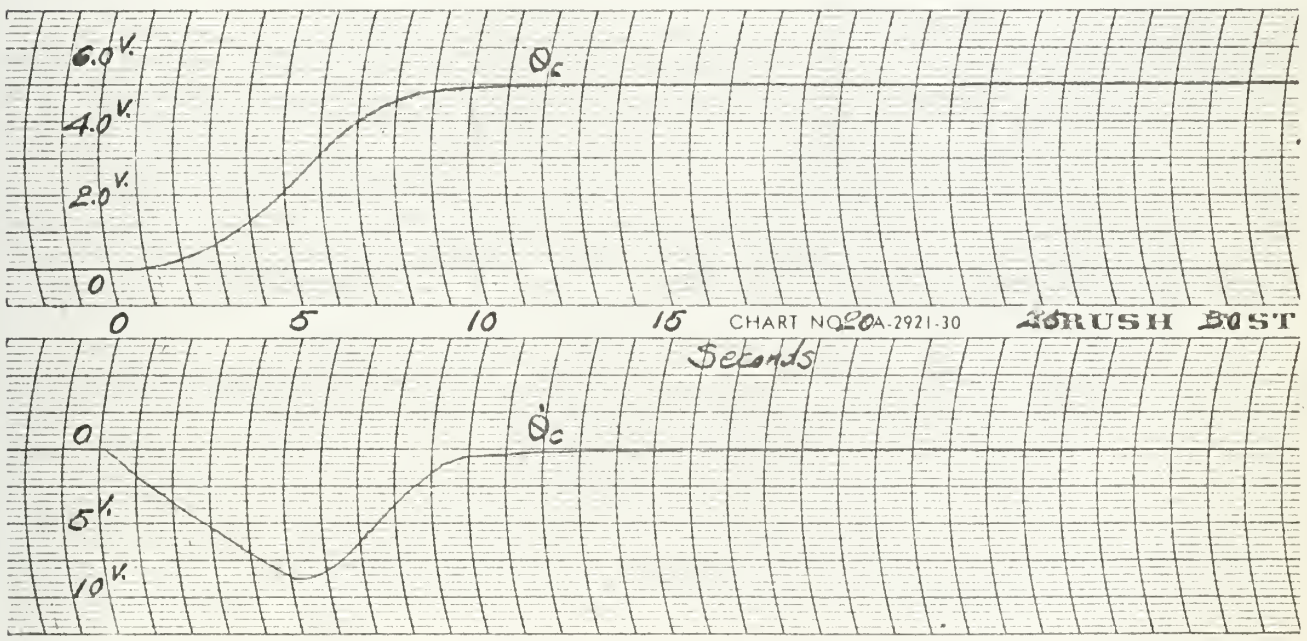


Fig. 21. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND -0.611 ERROR RATE FEEDBACK (2)

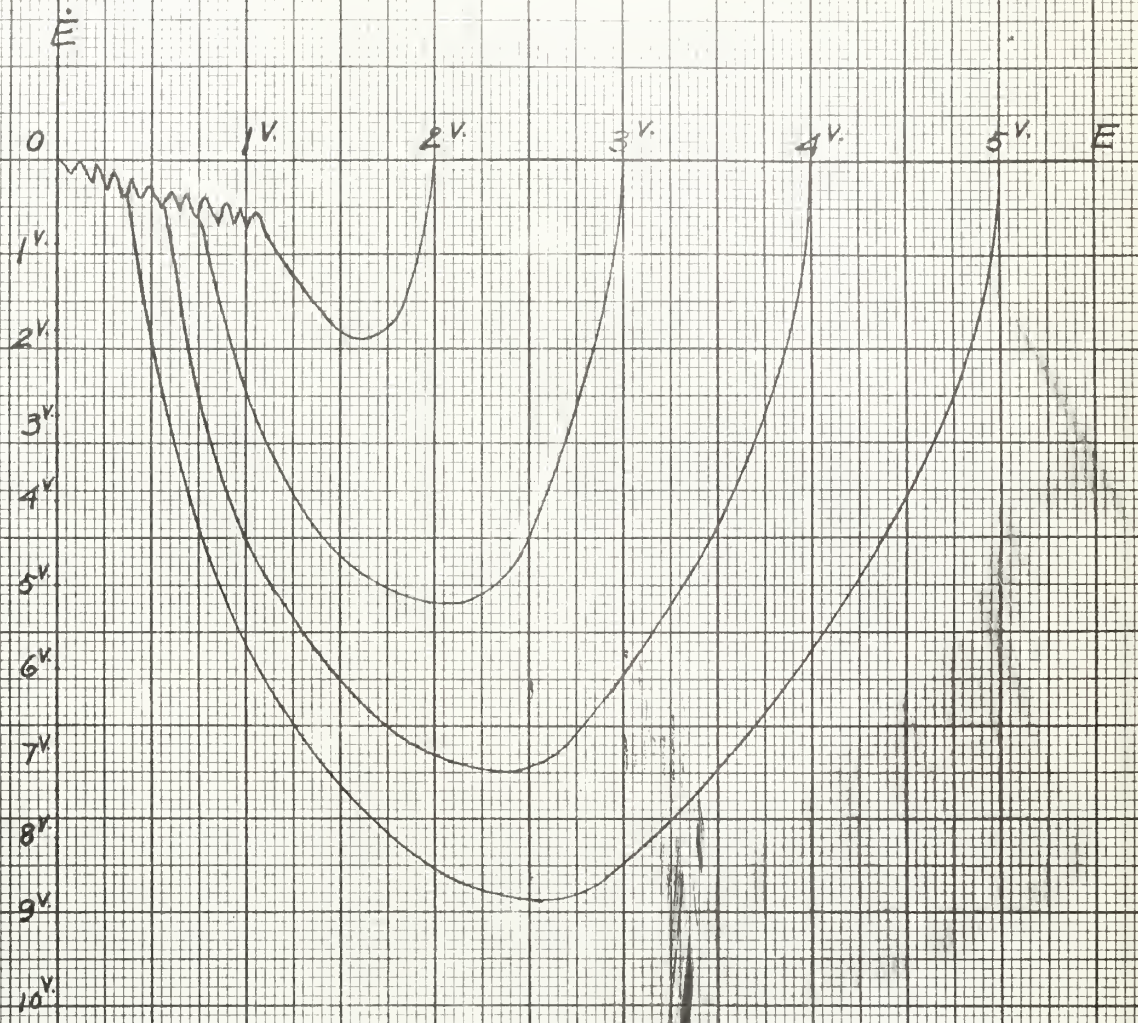


Fig. 22. PHASE PLANE TRAJETORIES OF SYSTEM WITH POSITION ERROR, AND −0.611 ERROR RATE FEEDBACK.

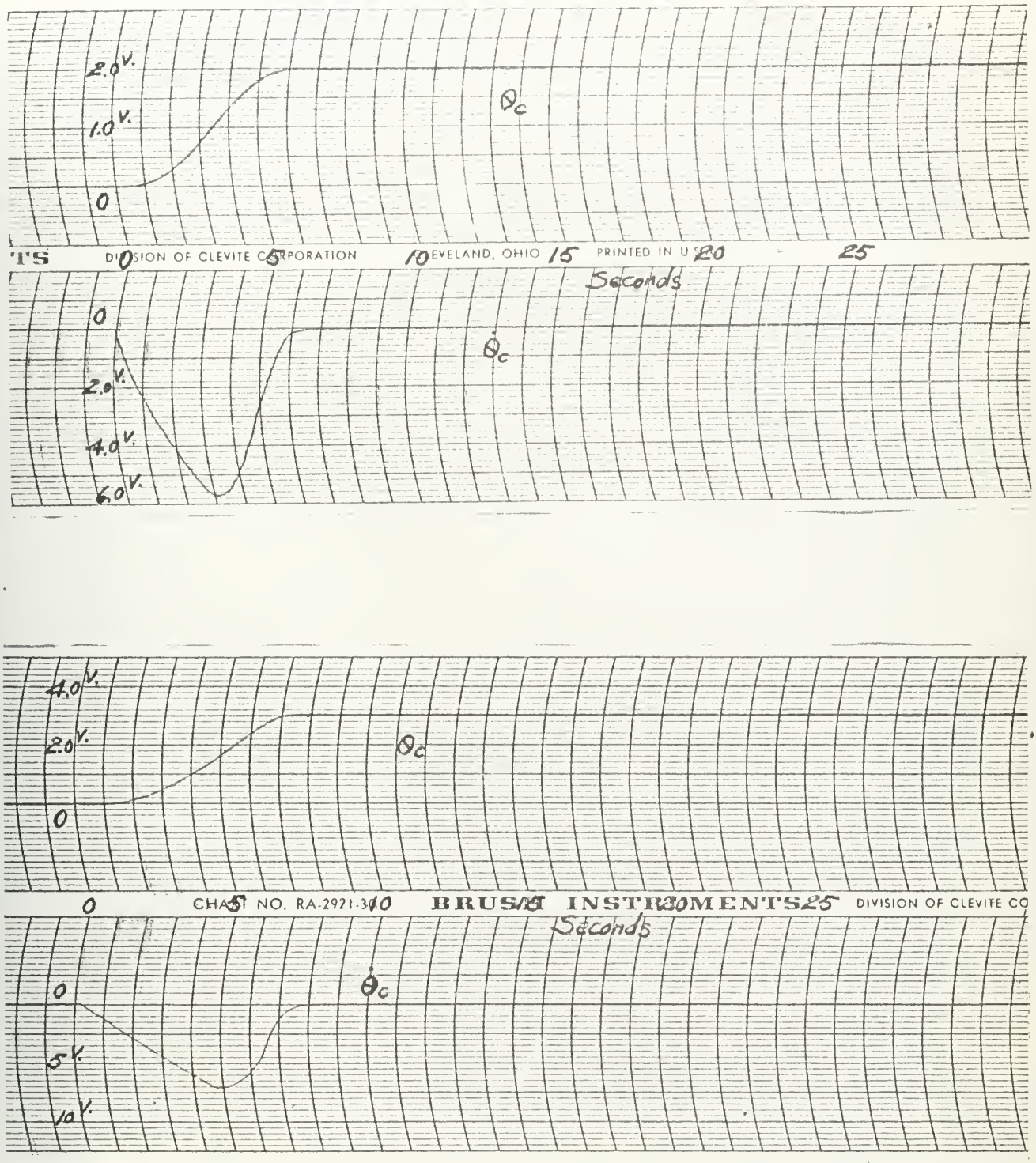


Fig. 23. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND −0.161 ERROR RATE FEEDBACK (1)

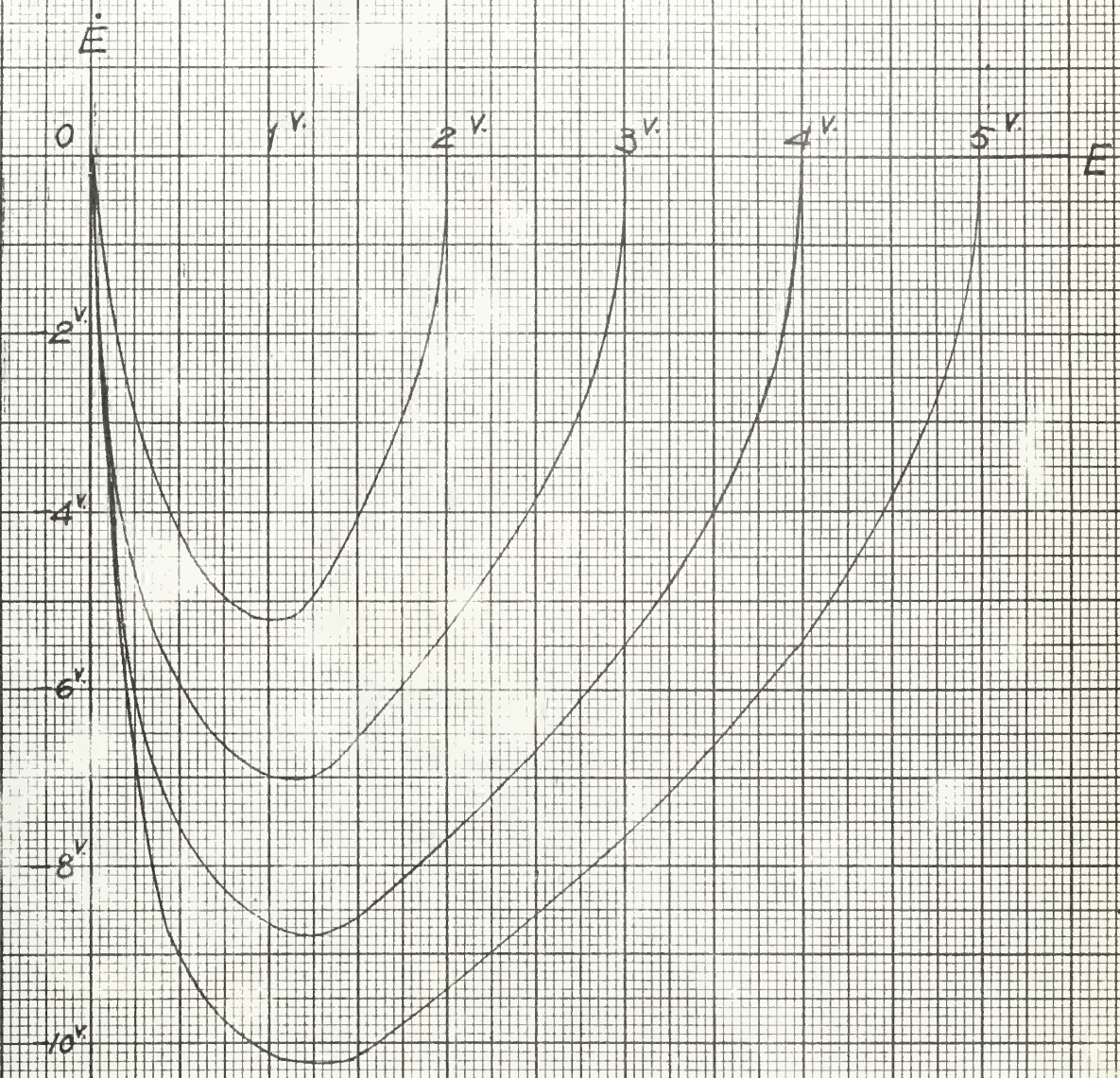


Fig. 25. PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR, AND −0.16 I ERROR RATE FEEDBACK

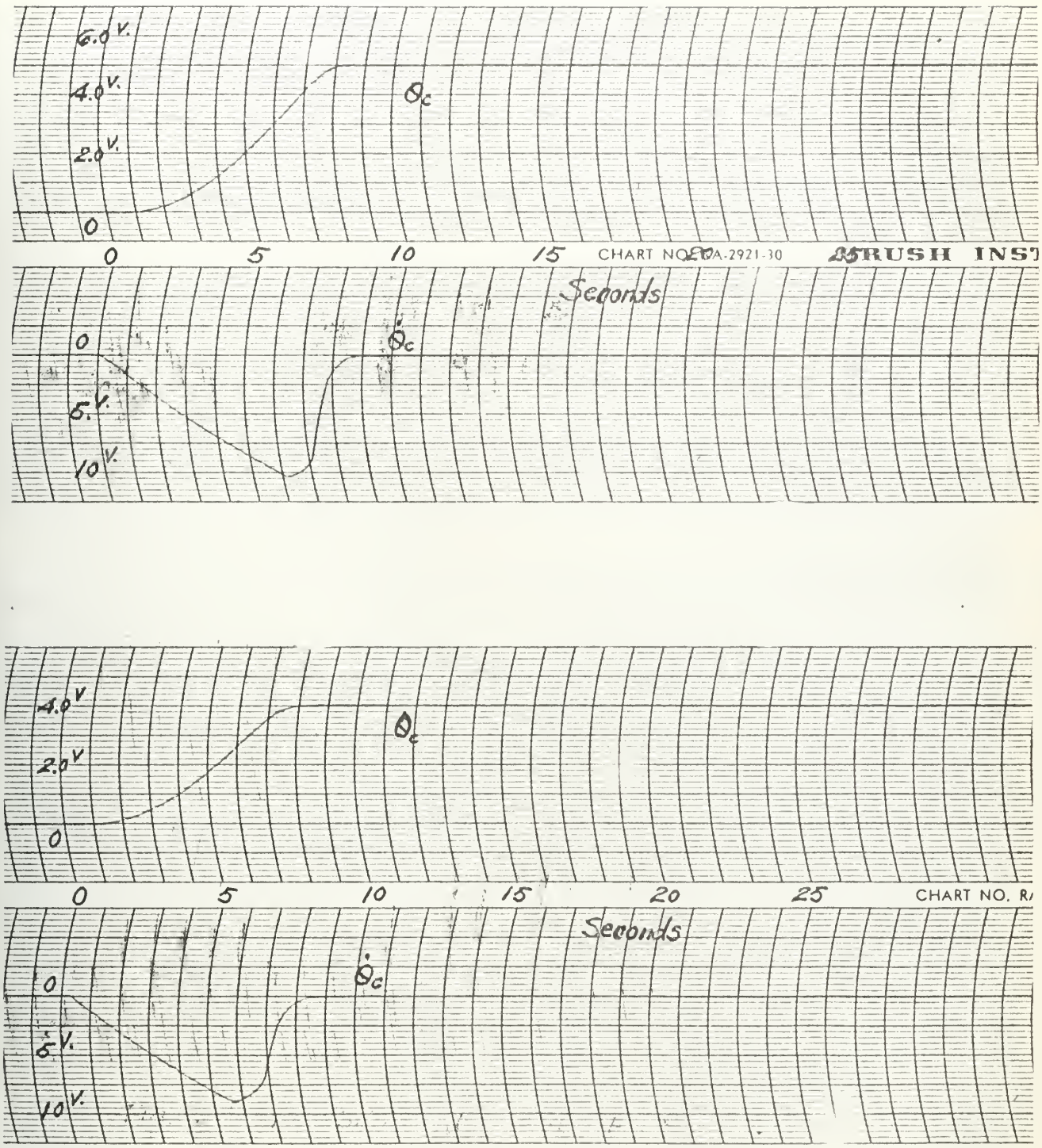


Fig. 24. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND −0.161 ERROR RATE FEEDBACK (2)

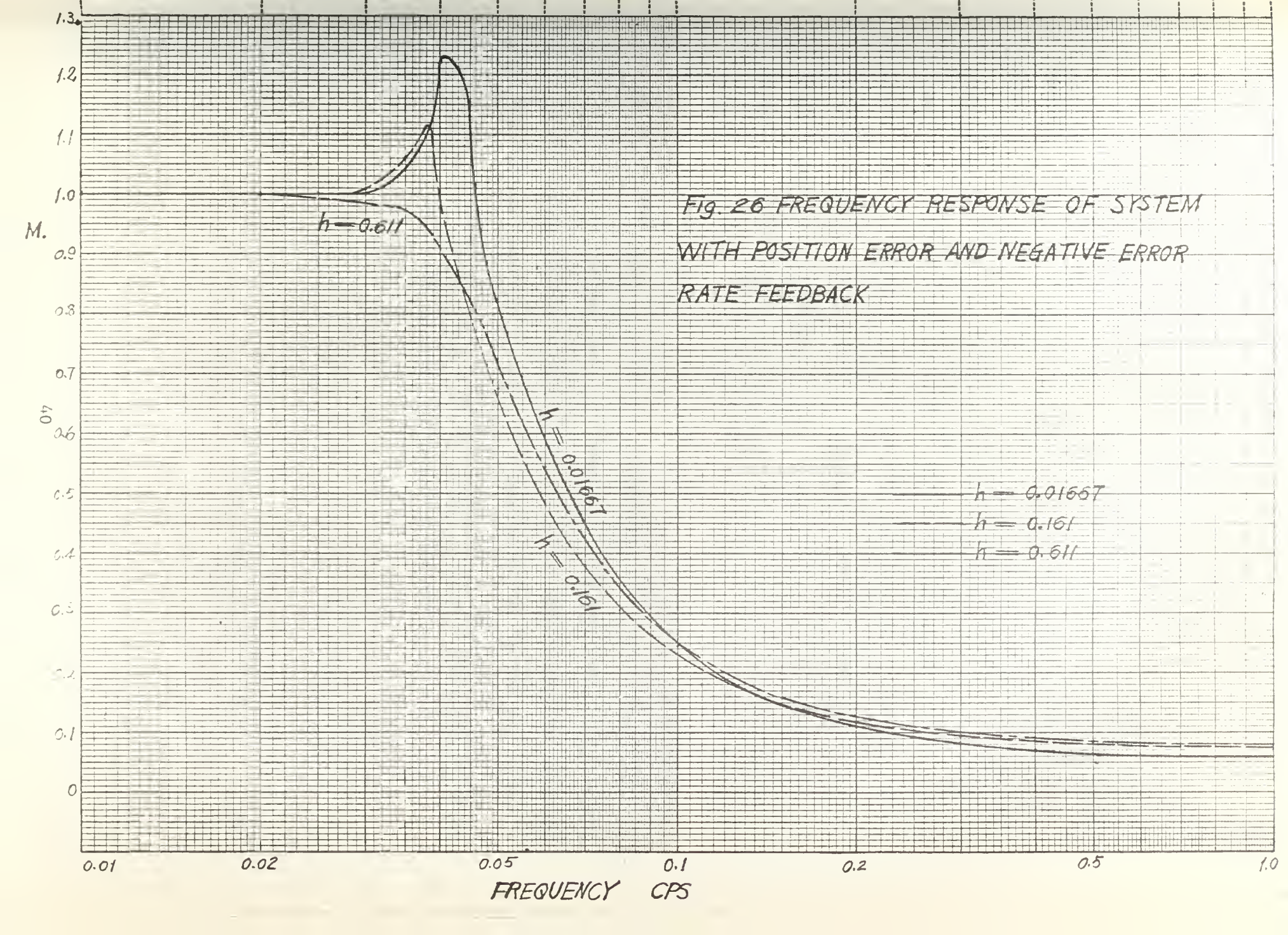


Fig. 26 FREQUENCY RESPONSE OF SYSTEM WITH POSITION ERROR AND NEGATIVE ERROR RATE FEEDBACK

6. Transient and Frequency Response of Natural System with Positive Error and Positive Error Rate Feedback Control.

As the natural system is a well-damped system, it does not take many oscillations before it reaches a steady state. However, for research purposes, we hope the experimental system is in a poor damped condition so that we may apply different kinds of compensation to make the system critically damped. From this point of view, the maximum allowable positive error rate feedback loop was added. The transient response of this system became more oscillatory. Fig. 27 and Fig. 28 shows the system transient response for large step-input. The transient responses for small step-displacement input are shown in Fig. 30 and Fig. 31. As we adjust the system, it becomes more unstable and oscillates more due to the positive error rate feedback. The overshoot is over twenty percent. Fig. 29 and Fig. 32 shows their phase plane trajectories. The switch line has been rotated about 5 degrees in clockwise direction. The limit circles will occur when positive error rate feedback coefficient is larger than 0.0102.

The frequency responses of positive error rate feedback system are shown in Fig. 33 and Fig. 34. It has higher overshoot than the natural system with error feedback at their resonance frequencies. The phase angle shifts faster than the natural system with increased frequency.

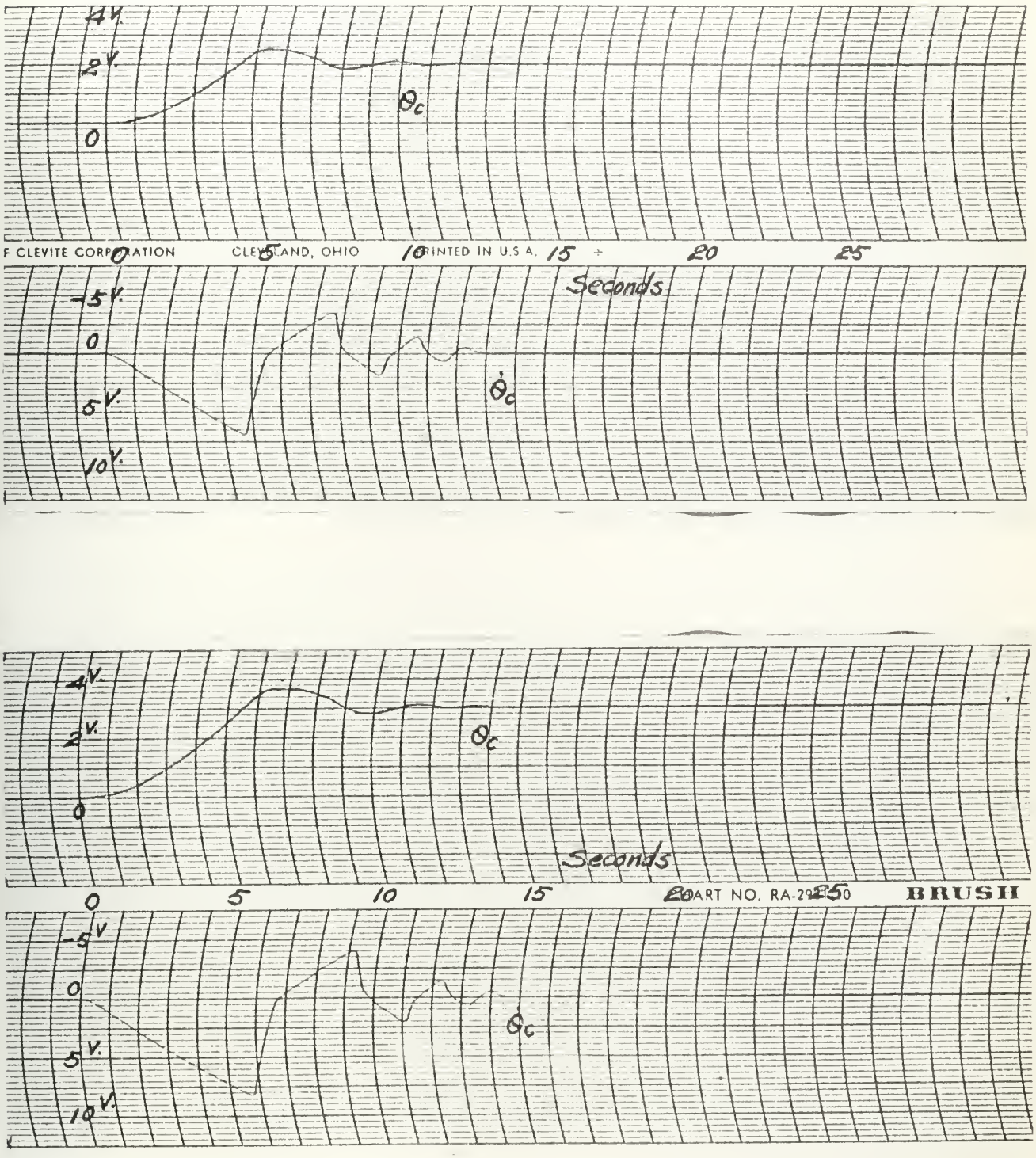


Fig. 27. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK FOR LARGE STEP INPUT (1)

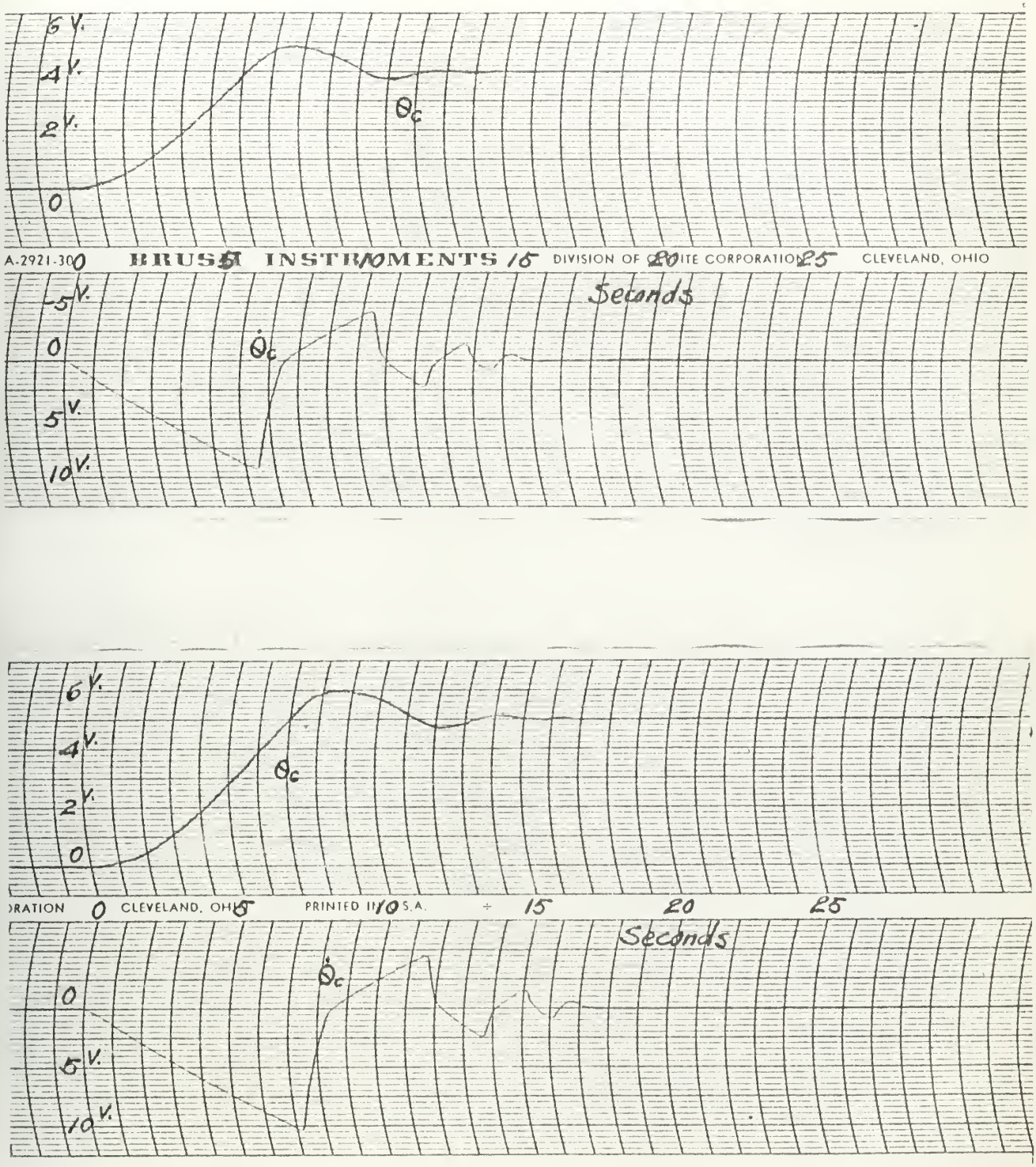


Fig. 28. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK FOR LARGE STEP INPUT (2)

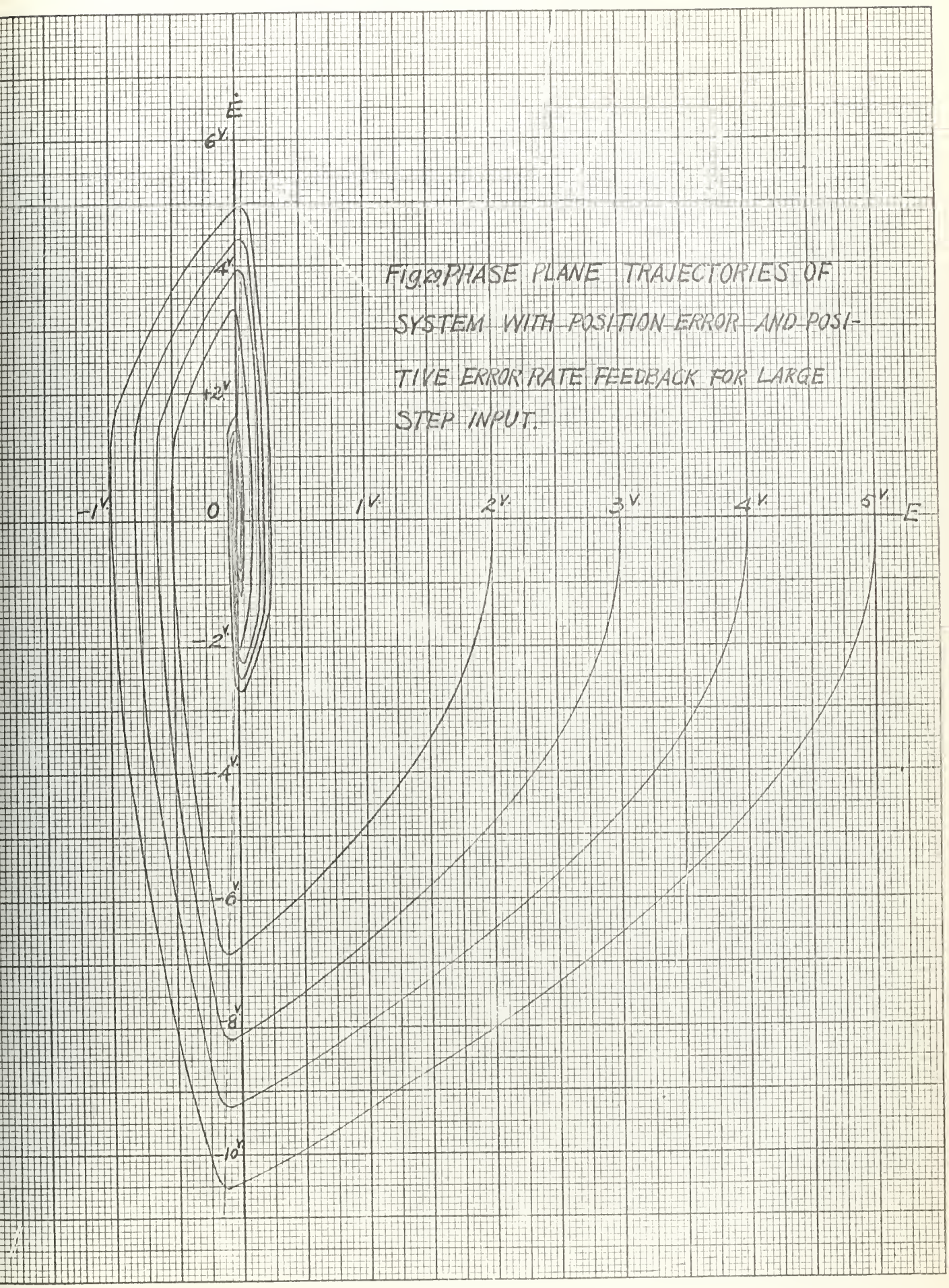


Fig.29 PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK FOR LARGE STEP INPUT.

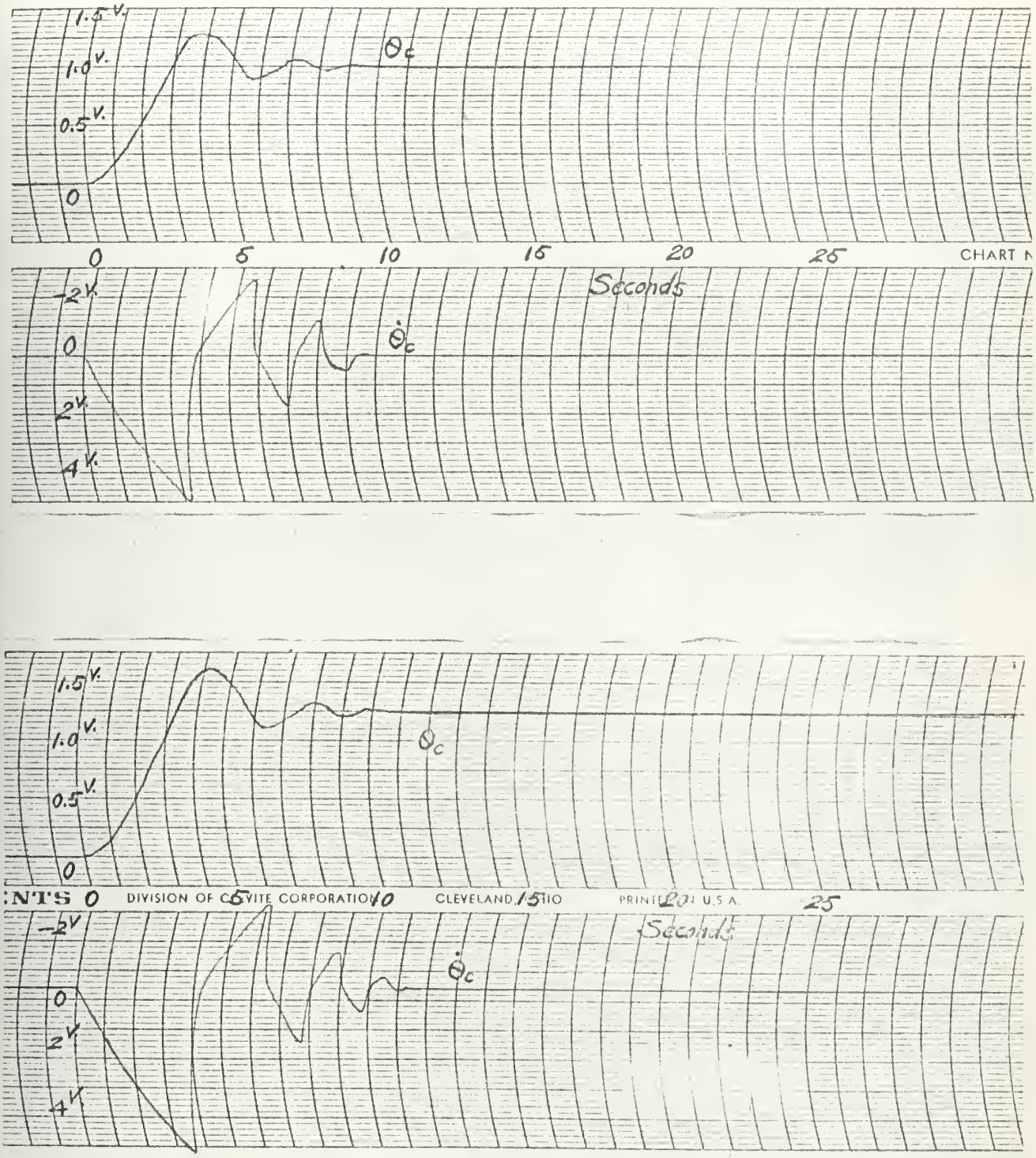


Fig. 30. TRANSIENT RESPONSES OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK FOR SMALL STEP INPUT (1)

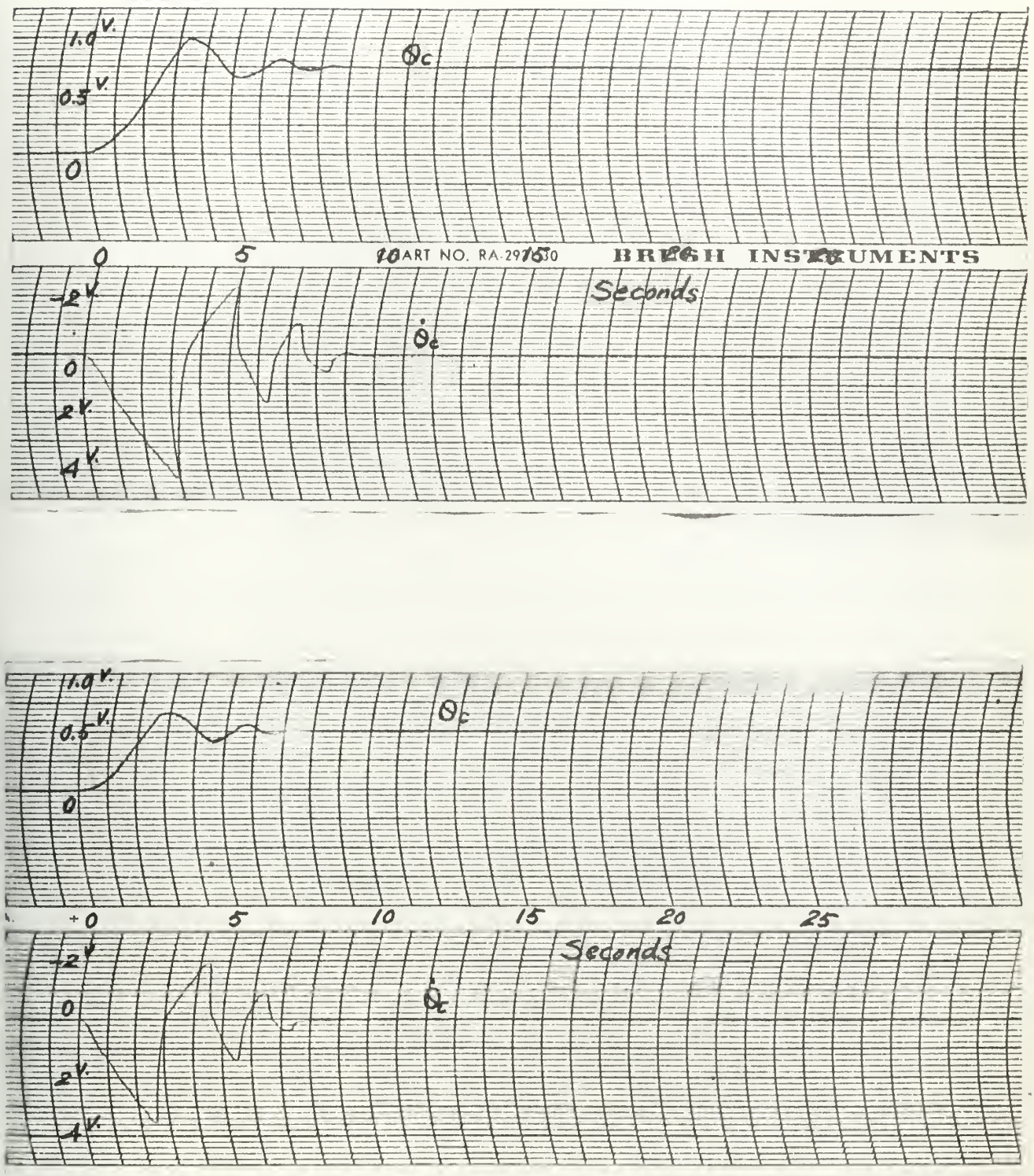


Fig. 31 TRANSIENT RESPONSES OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK FOR SMALL STEP INPUT (2)

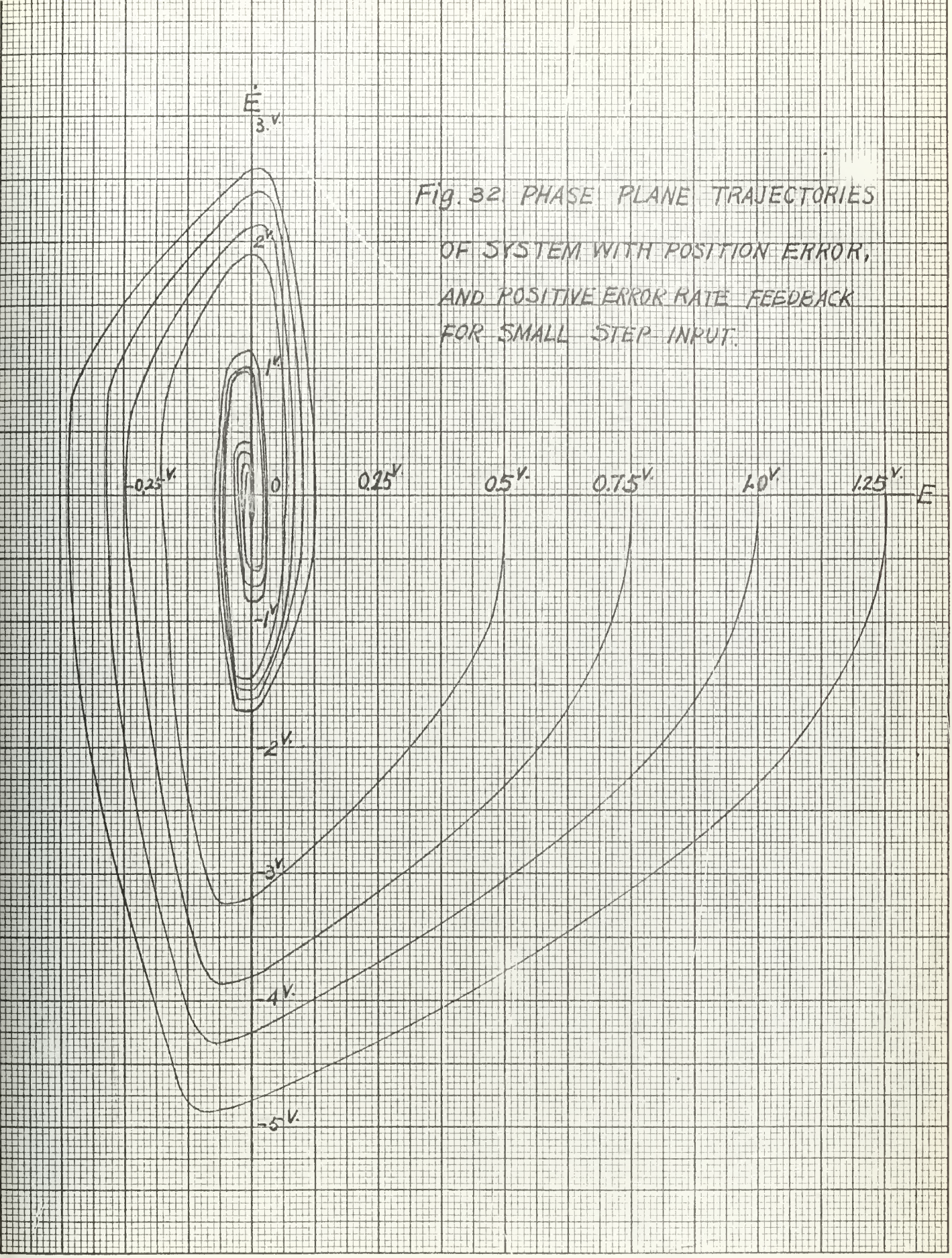


Fig. 32 PHASE PLANE TRAJECTORIES OF SYSTEM WITH POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK FOR SMALL STEP INPUT.

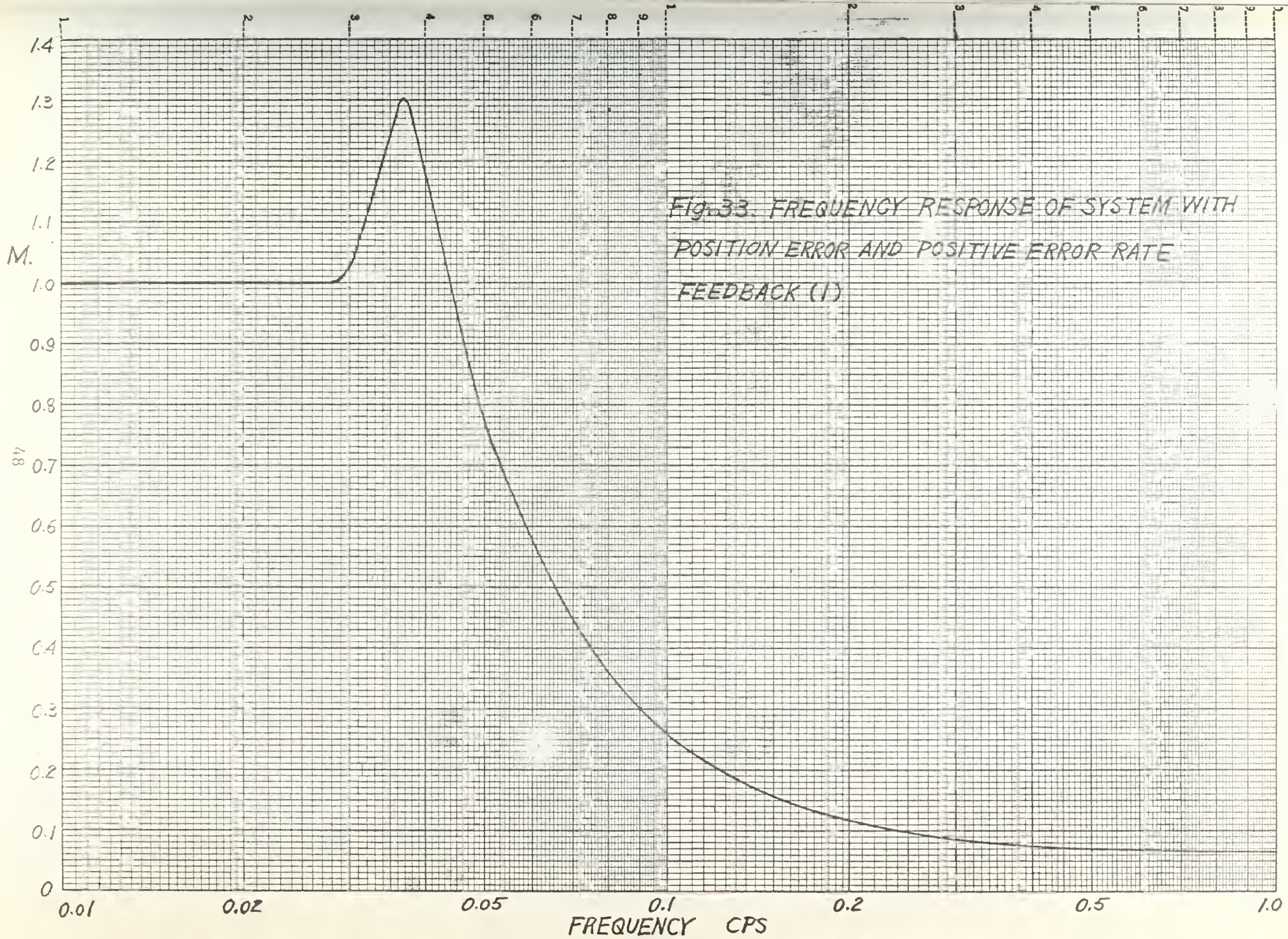


Fig. 33. FREQUENCY RESPONSE OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (1)

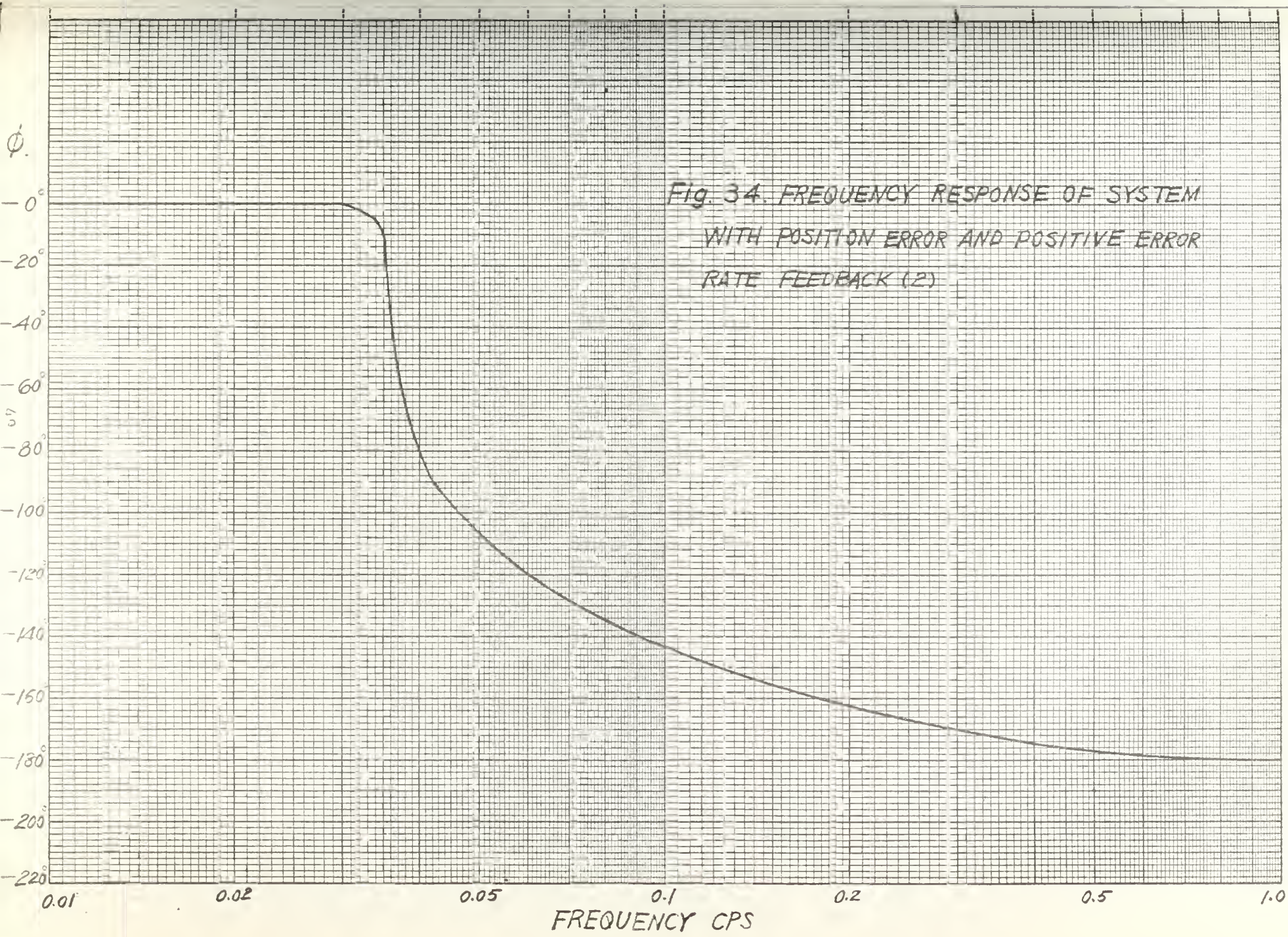


Fig. 34. FREQUENCY RESPONSE OF SYSTEM WITH POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2)

7. Transient and Frequency Response of Second System with Lead Network, Position Error, and Position Error Rate Feedback Control.

There are two most popular method used to compensate second order servomechanisms. These are negative tachometer feedback and lead network compensation. However the tachometer is not always available in the simple automatic control systems, therefore the lead network compensating has become more important. In addition the phase lead filters are easy to design and easy to adjust to meet different system requirements.

Section 3, "Filter Design"states that seven different filters have been used for compensating purposes. Their effect to the position of switch lines are listed in table 2.

These are the experimental results:

Fig. 35 and Fig. 36 show the transient responses of the system when it uses No. 1 filter for compensation. Fig. 37 shows their phase-plane trajectories. This is the best response we can get from the given system. The no. 1 filter helps the system to obtain optimum response. There is no overshoot and fast response. The switch line shifts about 24 degrees. This experimental result is in close agreement with the calculation result 22.5°. Fig. 38 and Fig. 39 show the system transient responses when it uses No. 2 filter for compensation. There is no overshoot. The settling time is longer compared to No. 1 filter. Fig. 40 shows their phase-plane trajectories. The comparison in frequency responses of No. 1 and No. 2 filters are shown in Fig. 41 and Fig. 42. No. 2 filter has higher overshoot at system resonant frequency than the No. 1 filter. No. 1 filter has larger leading angle than No. 2 filter. This is the first set of typical results from use of filters for compensation.

The second set of typical results from use of filters for system

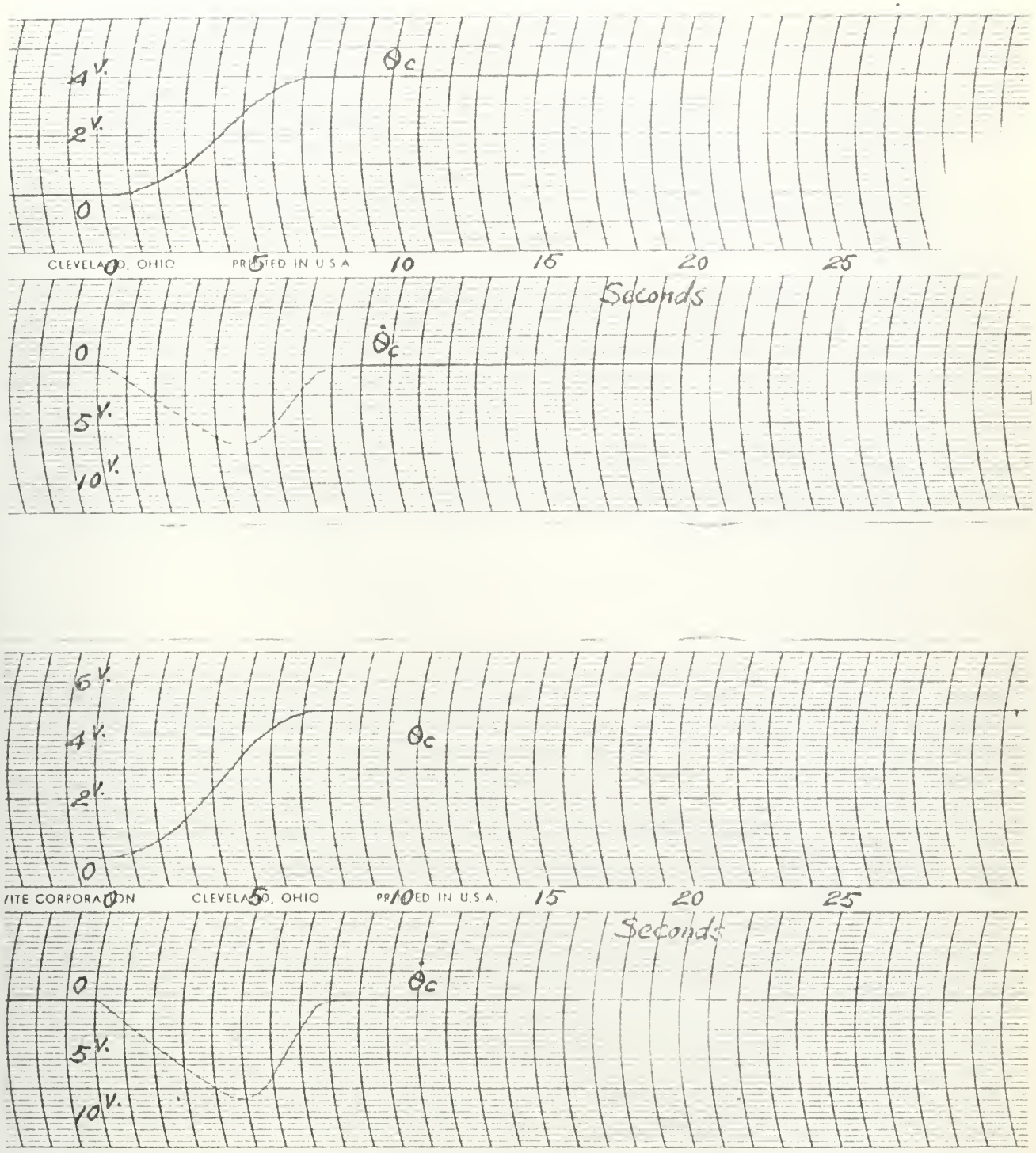


Fig. 35. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 1, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (1)

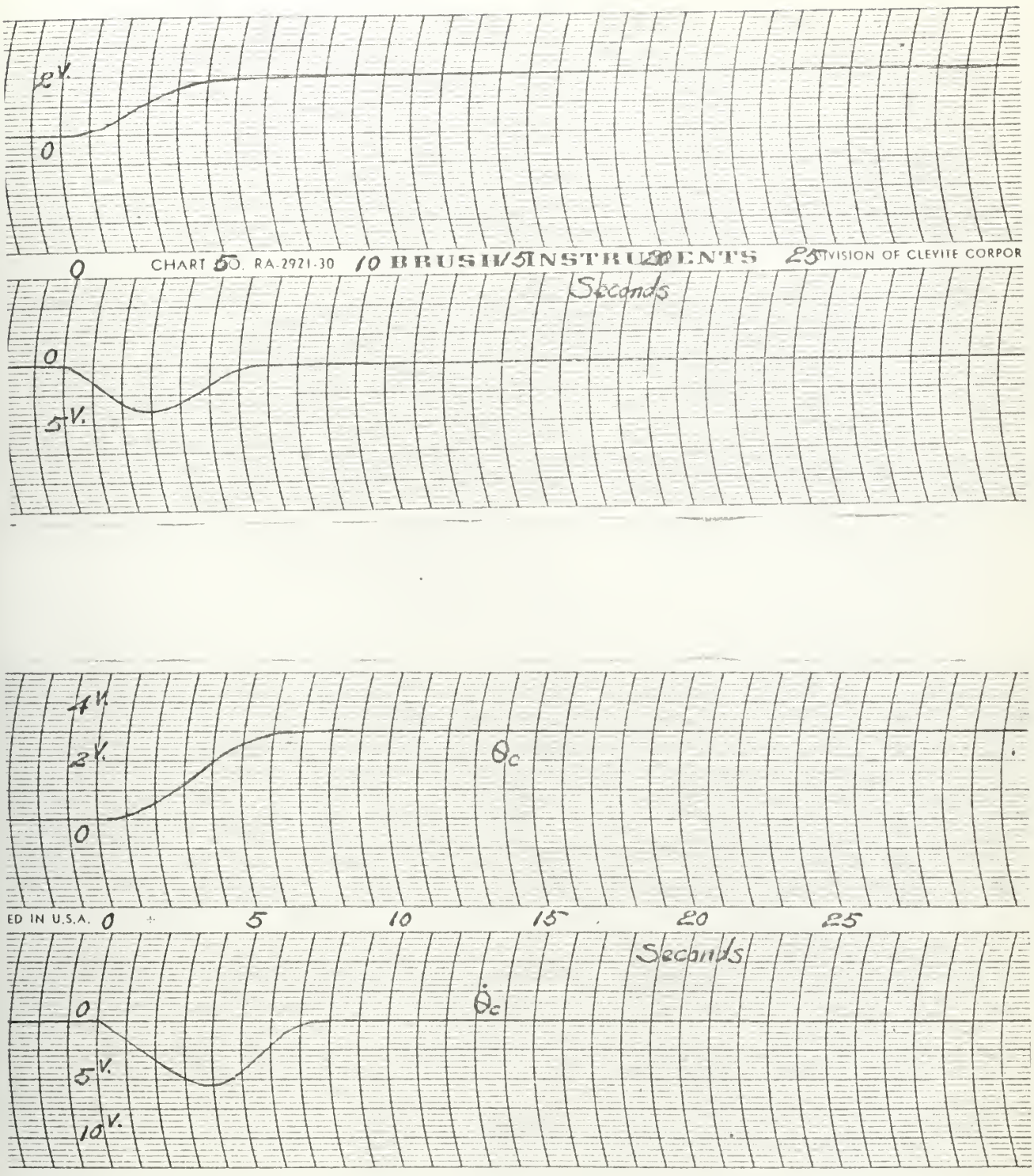


Fig. 36. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 1, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (2)

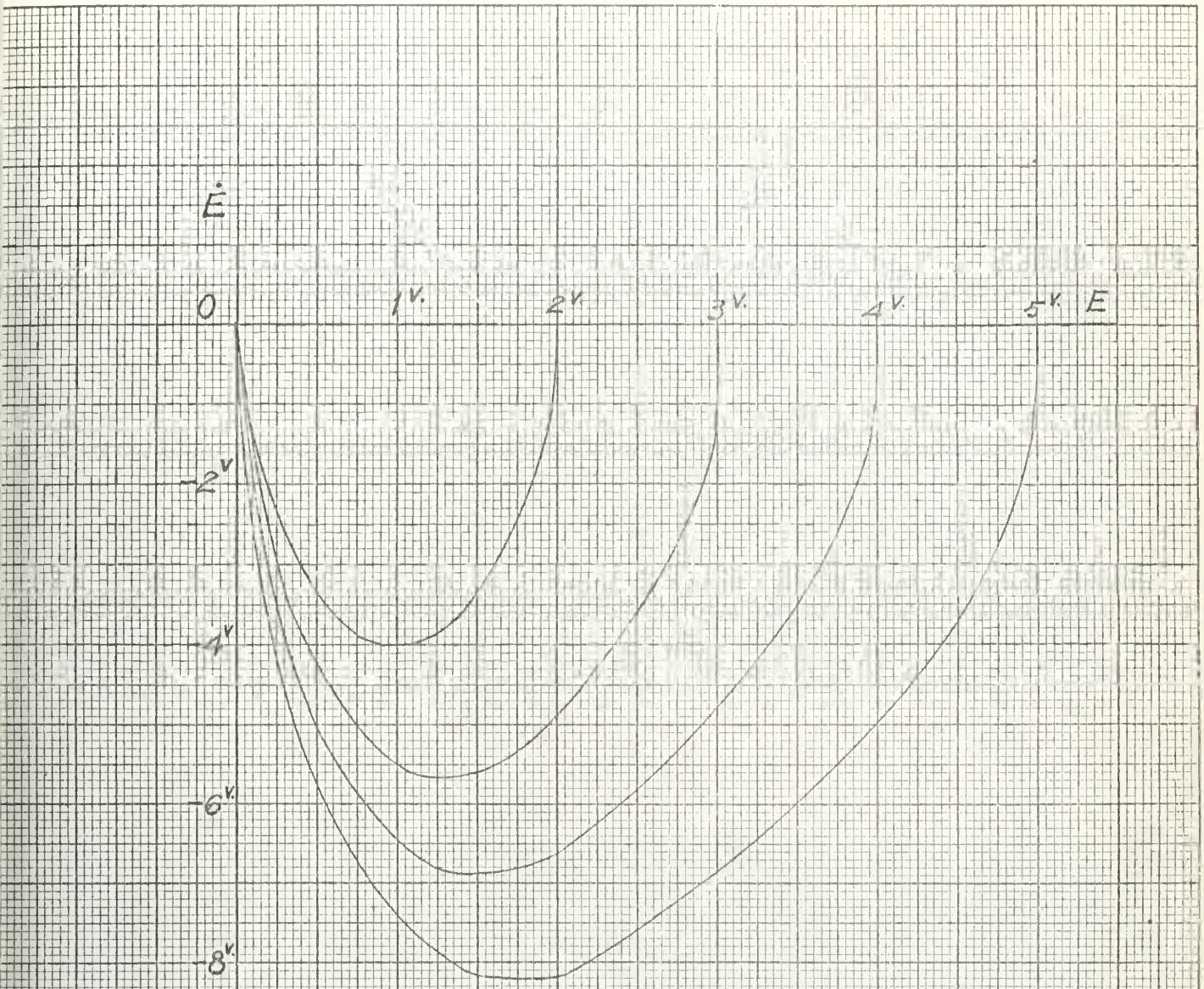


Fig. 37. PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER I., POSITION ERROR, POSITIVE ERROR RATE FEEDBACK.

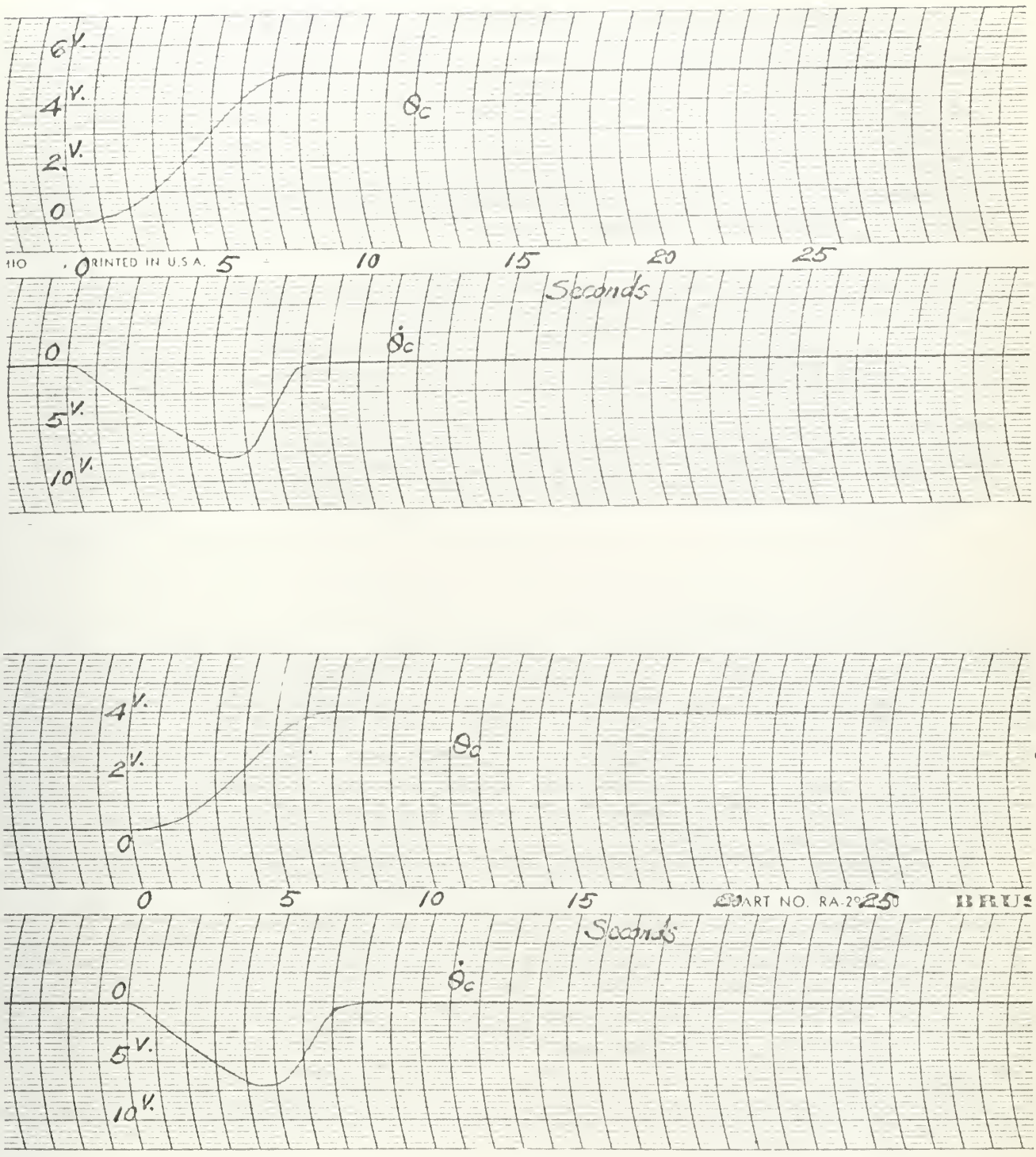


Fig. 38. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 2, POSITION ERROR, POSITIVE ERROR RATE FEEDBACK (1)

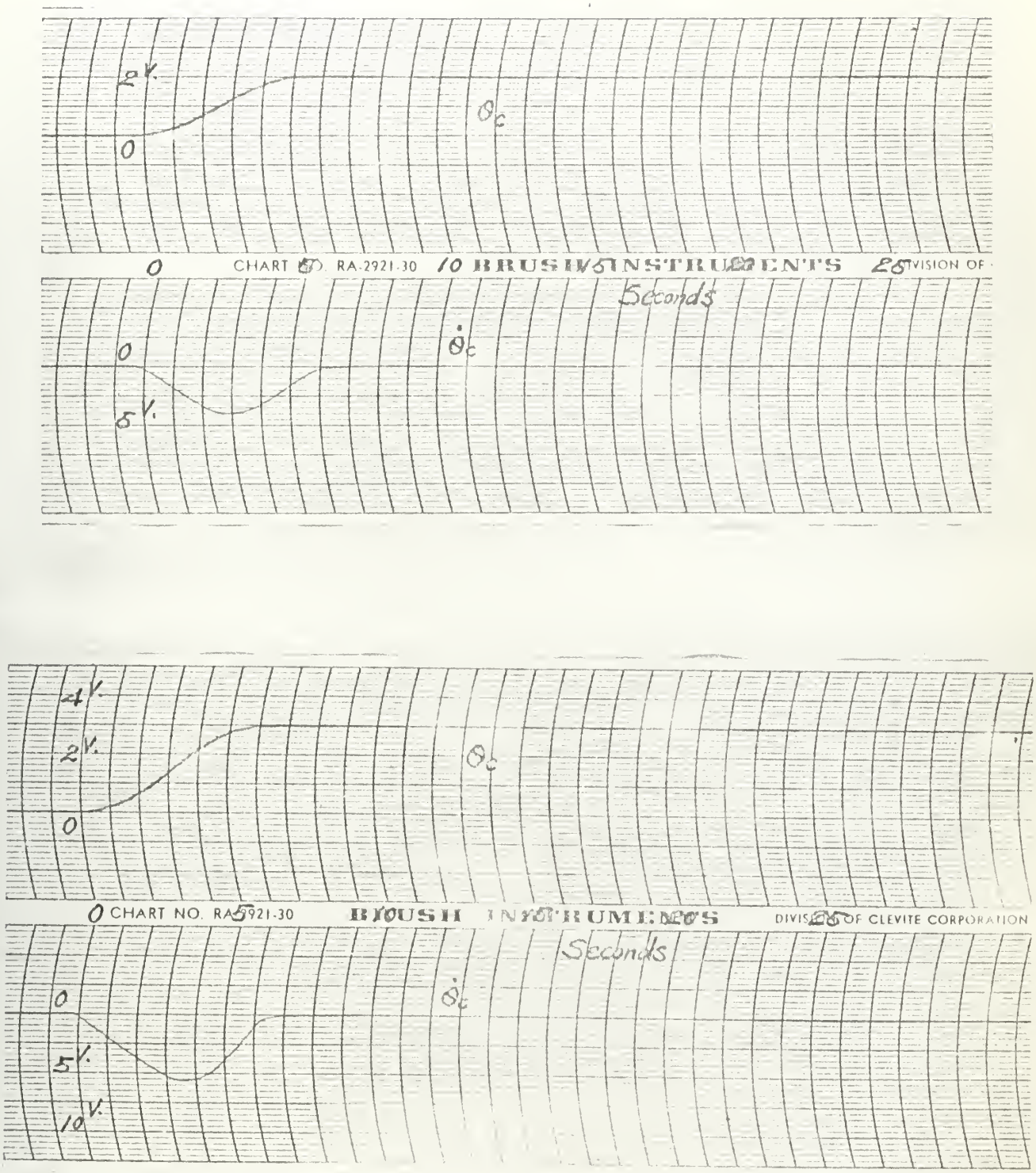


Fig. 39. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 2, POSITION ERROR, POSITIVE ERROR RATE FEEDBACK (2)

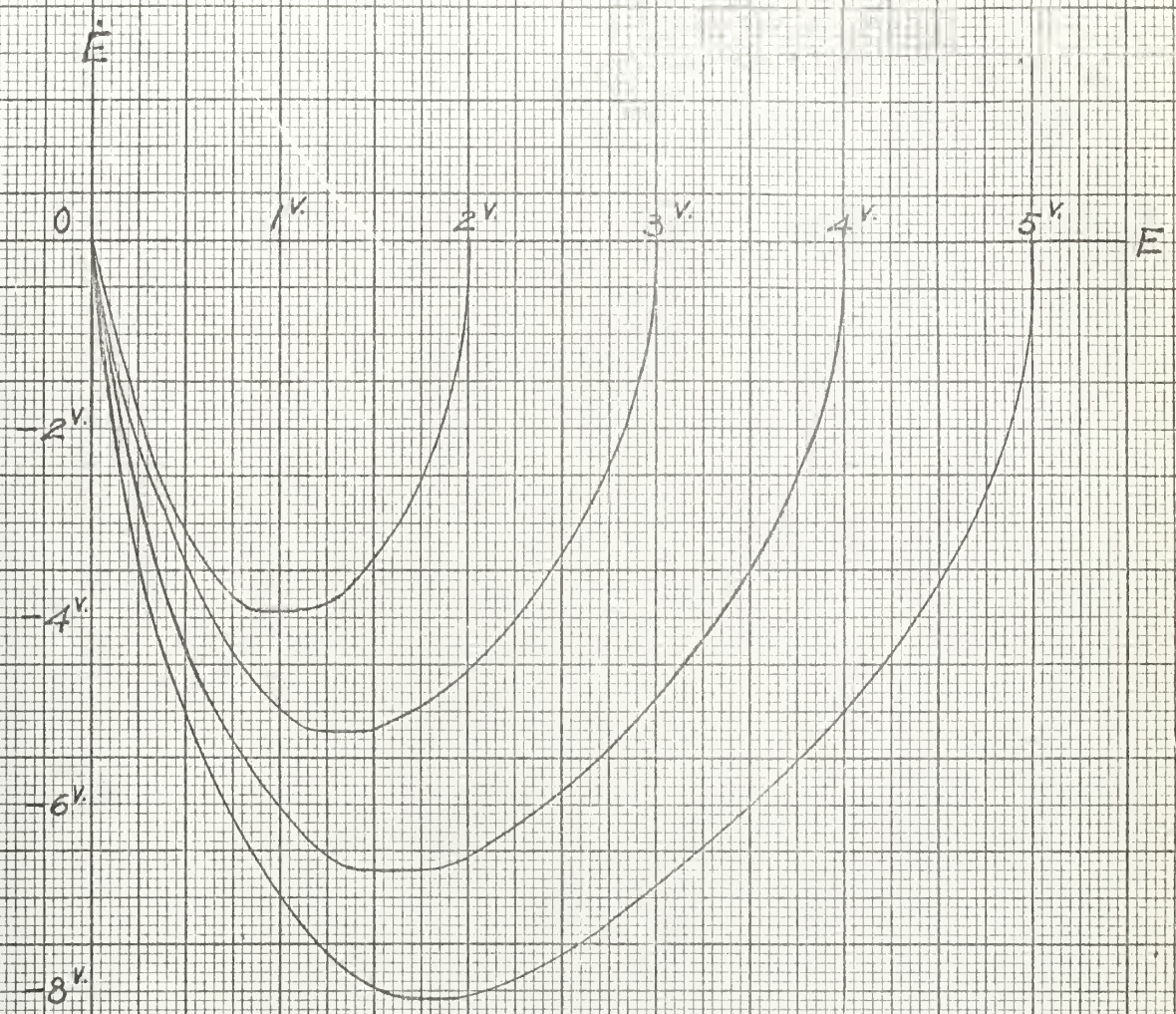


Fig. 40. PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 2, POSITION ERROR, POSITIVE ERROR RATE FEEDBACK.

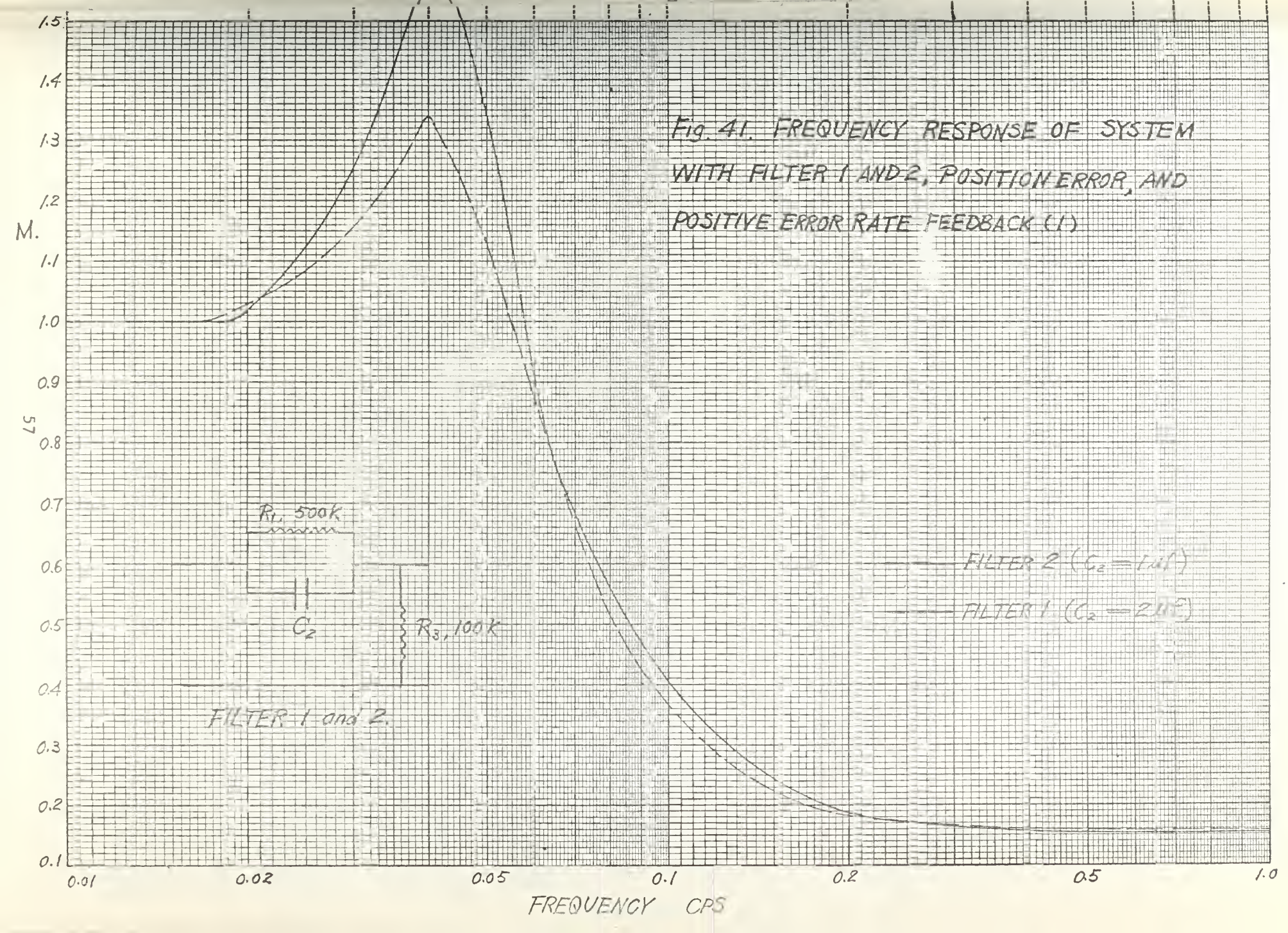


Fig. 41. FREQUENCY RESPONSE OF SYSTEM WITH FILTER 1 AND 2, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (1)
M.
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01
0.02
0.05
0.1
0.2
0.5
1.0
FREQUENCY CPS
R1, 500K
C2
R3, 100K
FILTER 1 and 2.
FILTER 2 (C2 = 1 μf)
FILTER 1 (C2 = 2 μf)

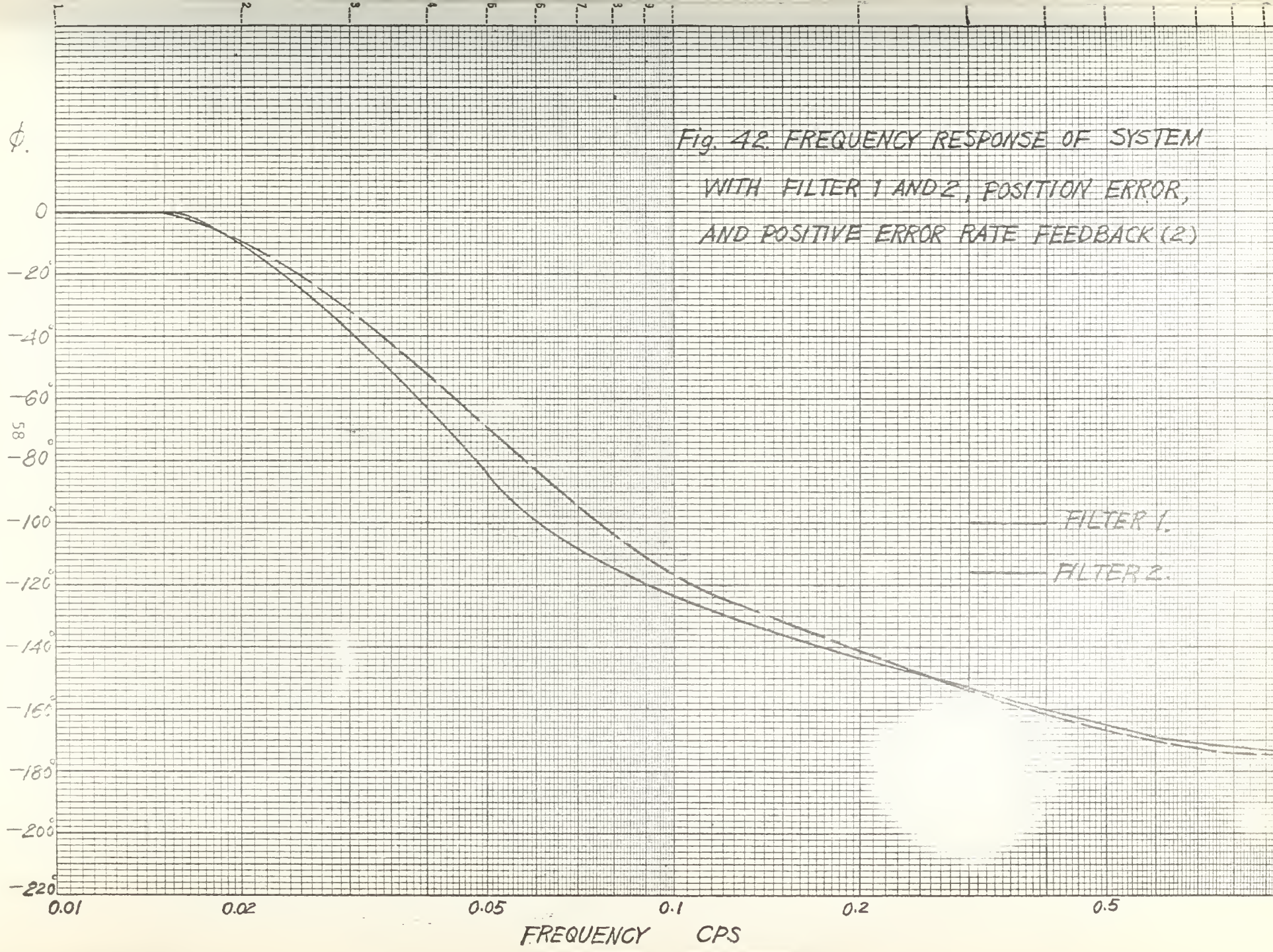


Fig. 42. FREQUENCY RESPONSE OF SYSTEM WITH FILTER 1 AND 2, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (2)
φ.
0
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
-200°
-220°
58
FILTER 1.
FILTER 2.
0.01
0.02
0.05
0.1
0.2
0.5
FREQUENCY CPS

compensation are shown in Figures [illegible] using these sets of filters. [illegible] compared with the other two typical results. [illegible] show the system with No. 3 filter transient response. [illegible] time to reach the final steady state as it operates on underdamped condition. Figures 46 and 47 show the No. 4 filter transient responses. Figures 45 and 48 show the phase-plane trajectories of the two filters. As the switching times are too early in No. 3 and No. 4 filters, the response has a long tail due to chattering phenomenon around the origin region. The frequency responses of these two filter compensations are shown in Fig. 49 and Fig. 50. The system with No. 3 filter has higher overshoot at resonant frequency. These results agree with their transient response records. The one with the higher overshoot during resonance frequency has lower transient response.

Filter No. 5, filter No. 6 and filter No. 7 were used in system compensating tests to get third typical results. These three filters all have later switch times. In other words, they do not shift the system switch line large enough to reach optimum response position, therefore the system has transient overshoot response. The degree of overshoot depends upon the first switching time. The transient responses of these three filters are shown in Fig. 51 and 52, Fig. 56 and 57, Fig. 59 and 60, respectively. Their phase plane trajectories are shown in Fig. 53, Fig. 58 and Fig. 61. With No. 5 filter compensating the system frequency responses are shown in Figures 54 and 55.

The above three typical effects of filter compensation are in agreement with Dr. Kan Chen's experimental results published in "Application and Industry," Nov. 1959, pp 337-340.

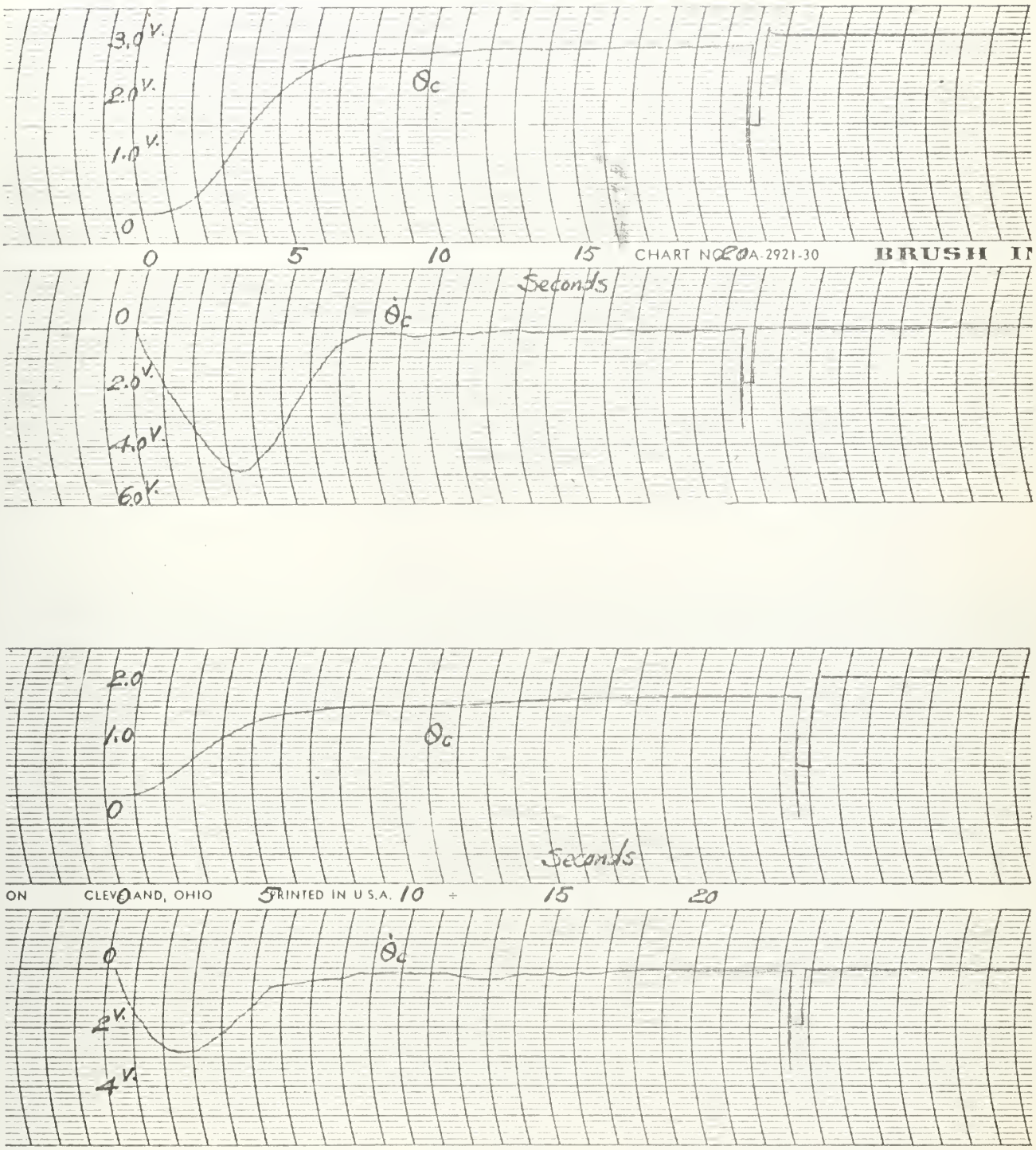


Fig. 43 TRANSIENT RESPONSE OF SYSTEM WITH FILTER 3, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (1).

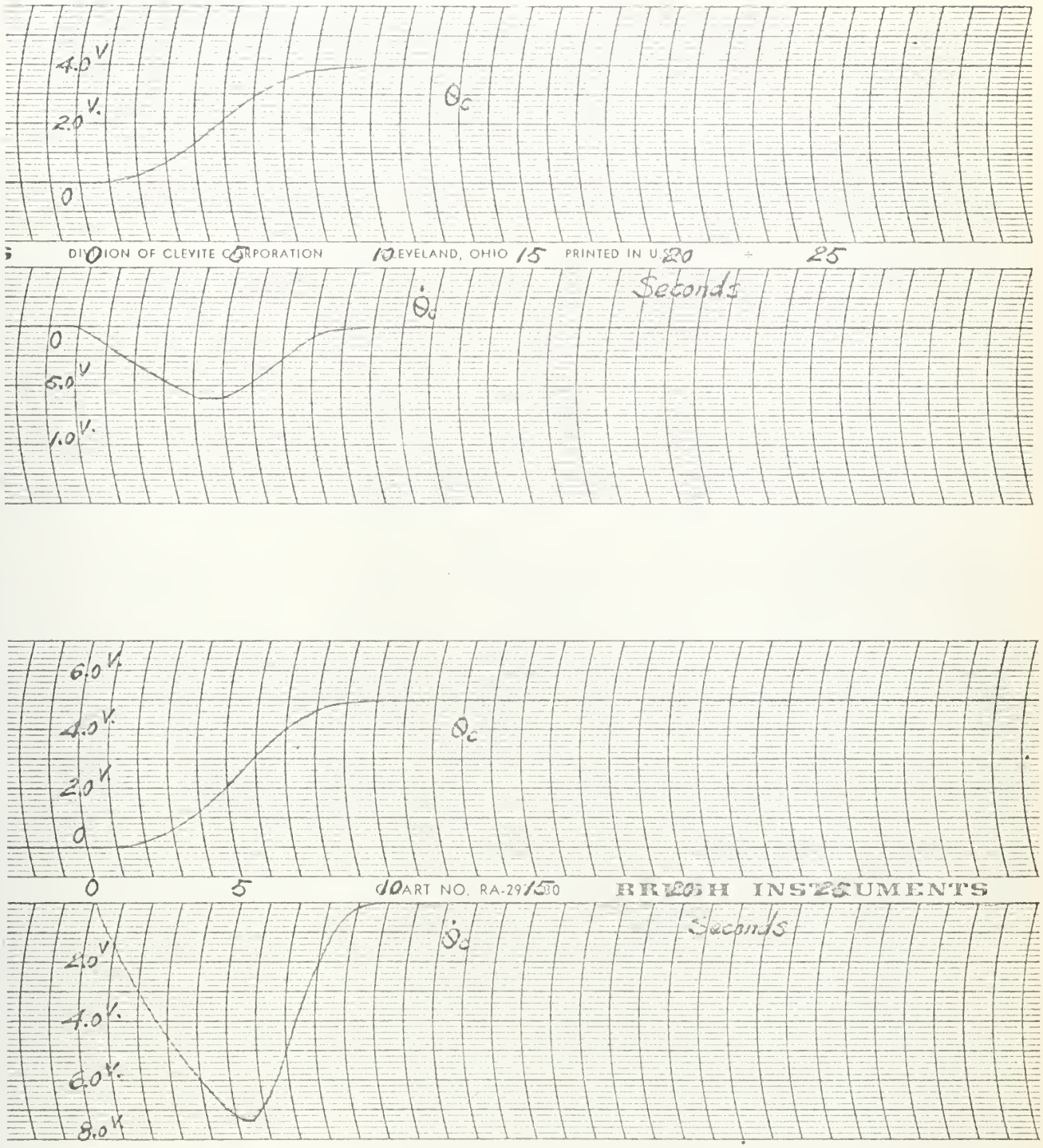
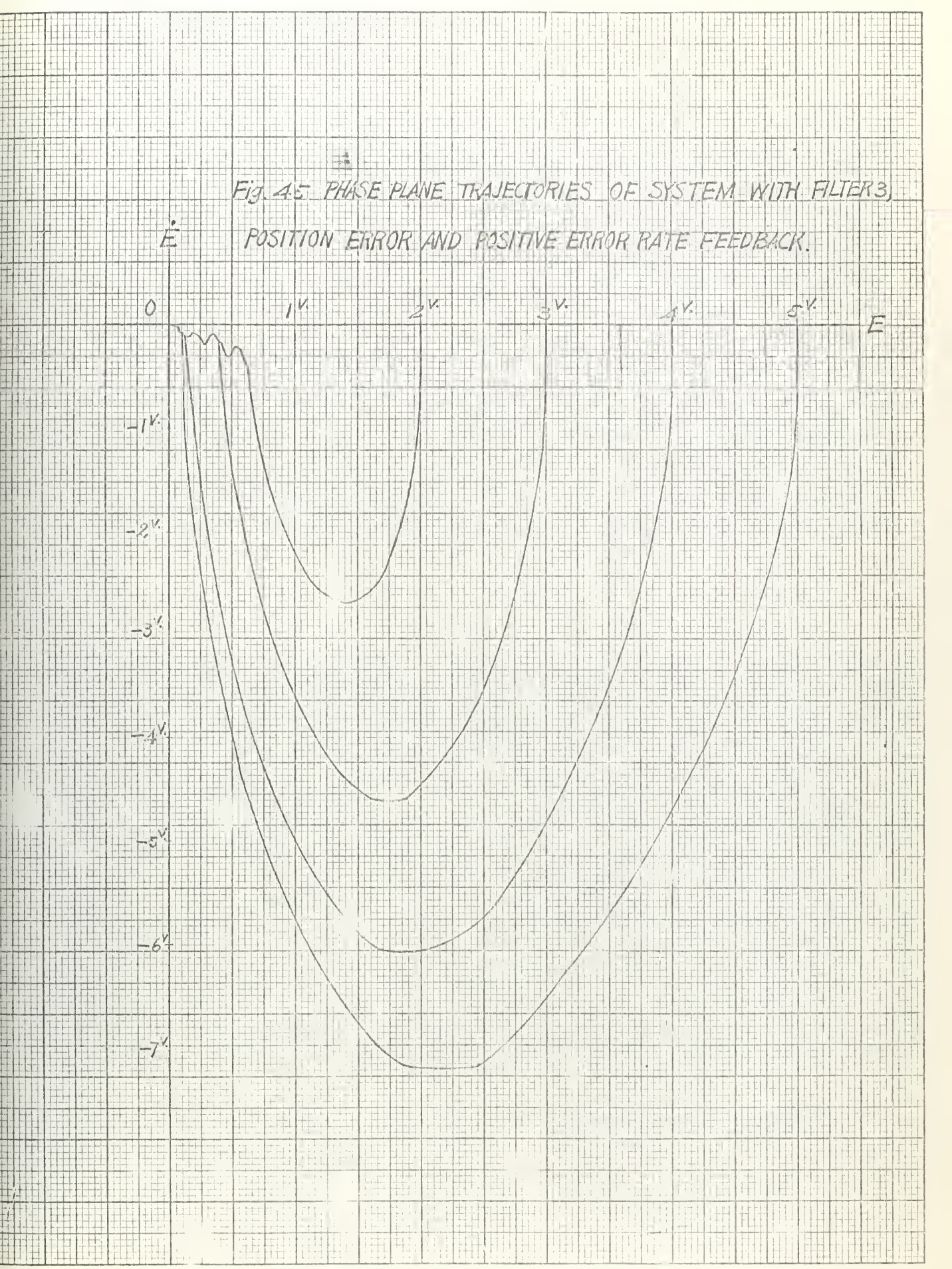


Fig. 44. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 3, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (2).

Fig. 45 PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 3, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK.



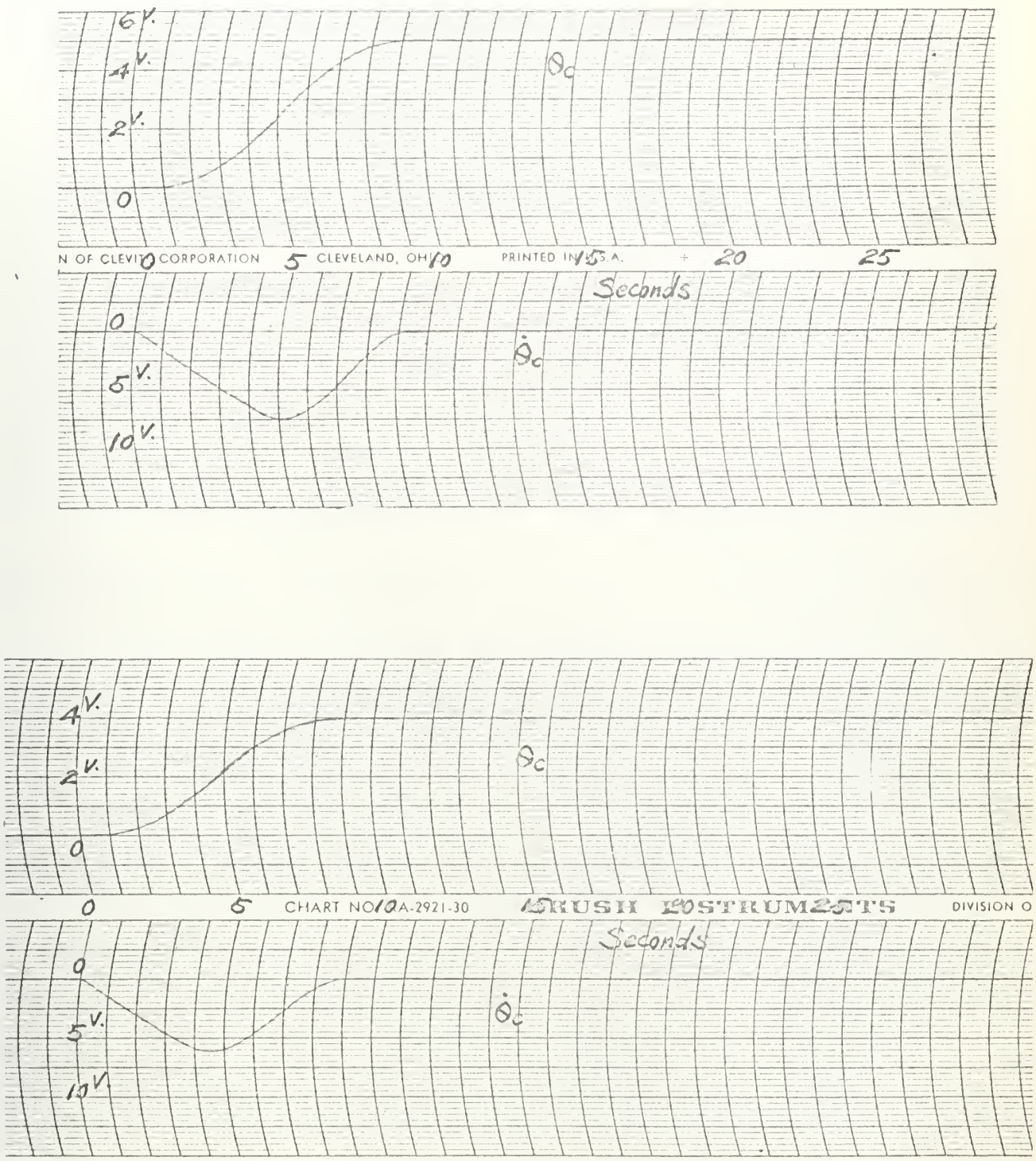
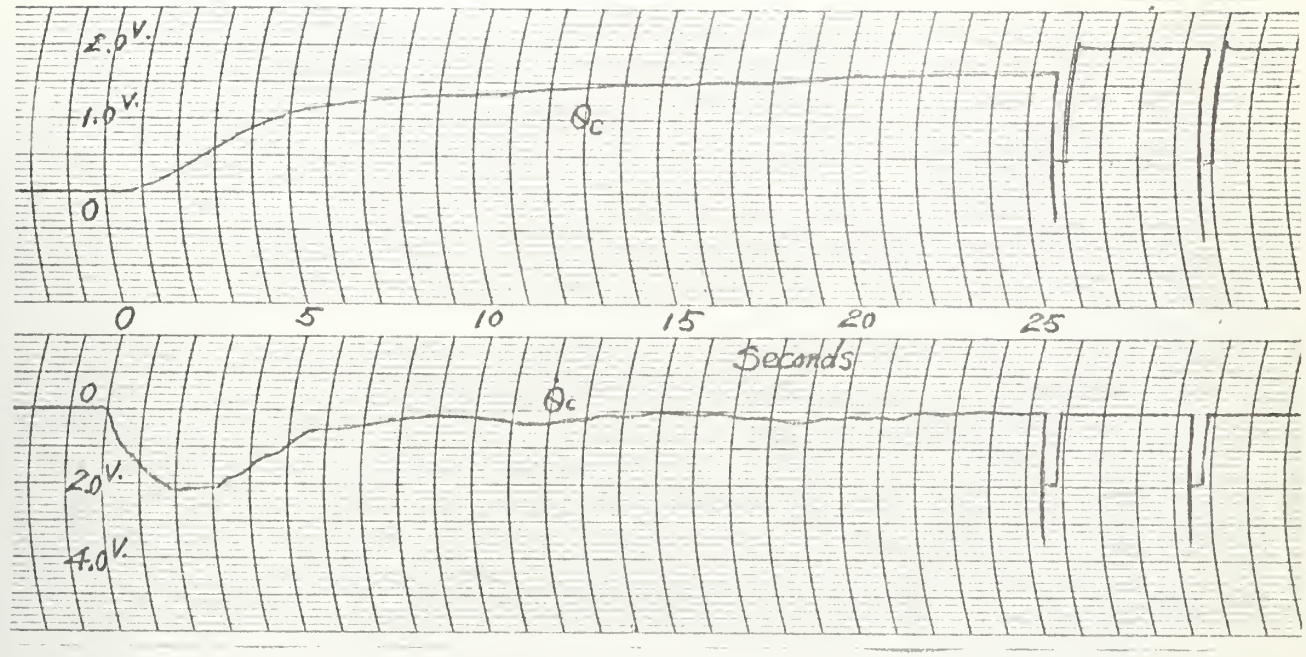


Fig. 46. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 4, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (1).



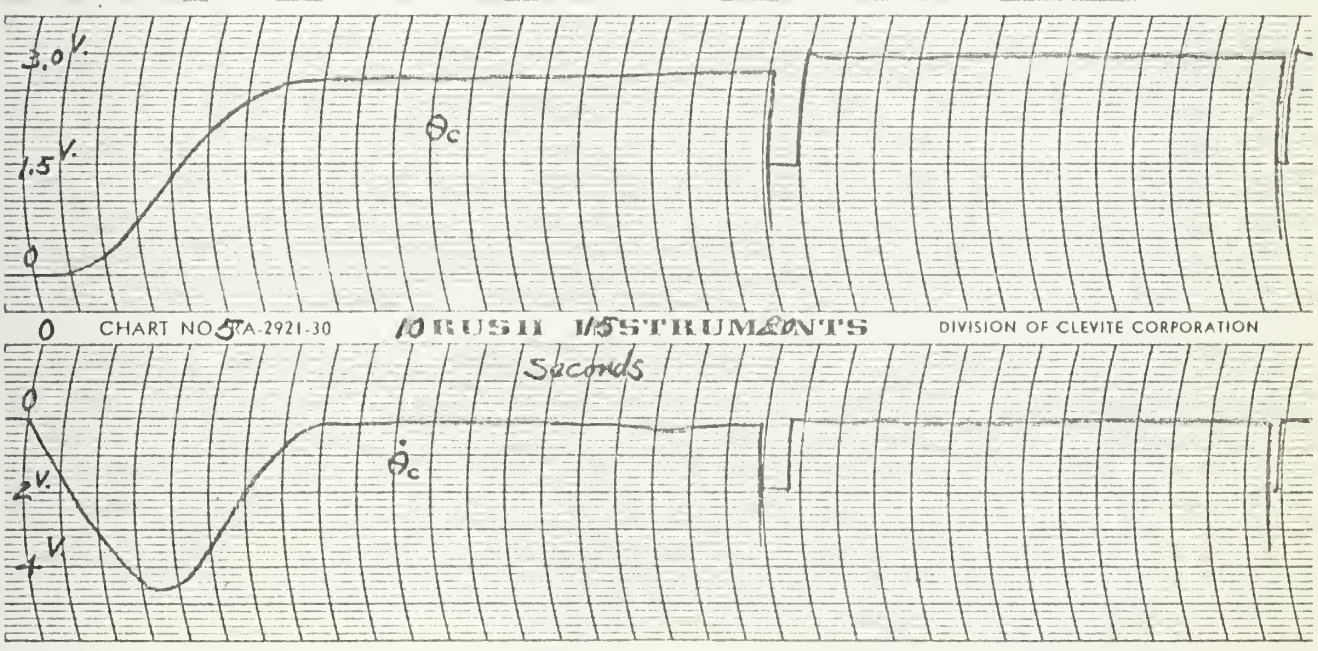


Fig. 47. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 4, POSITION ERROR, AND POSITIVE ERROR RATE FEEDBACK (2).

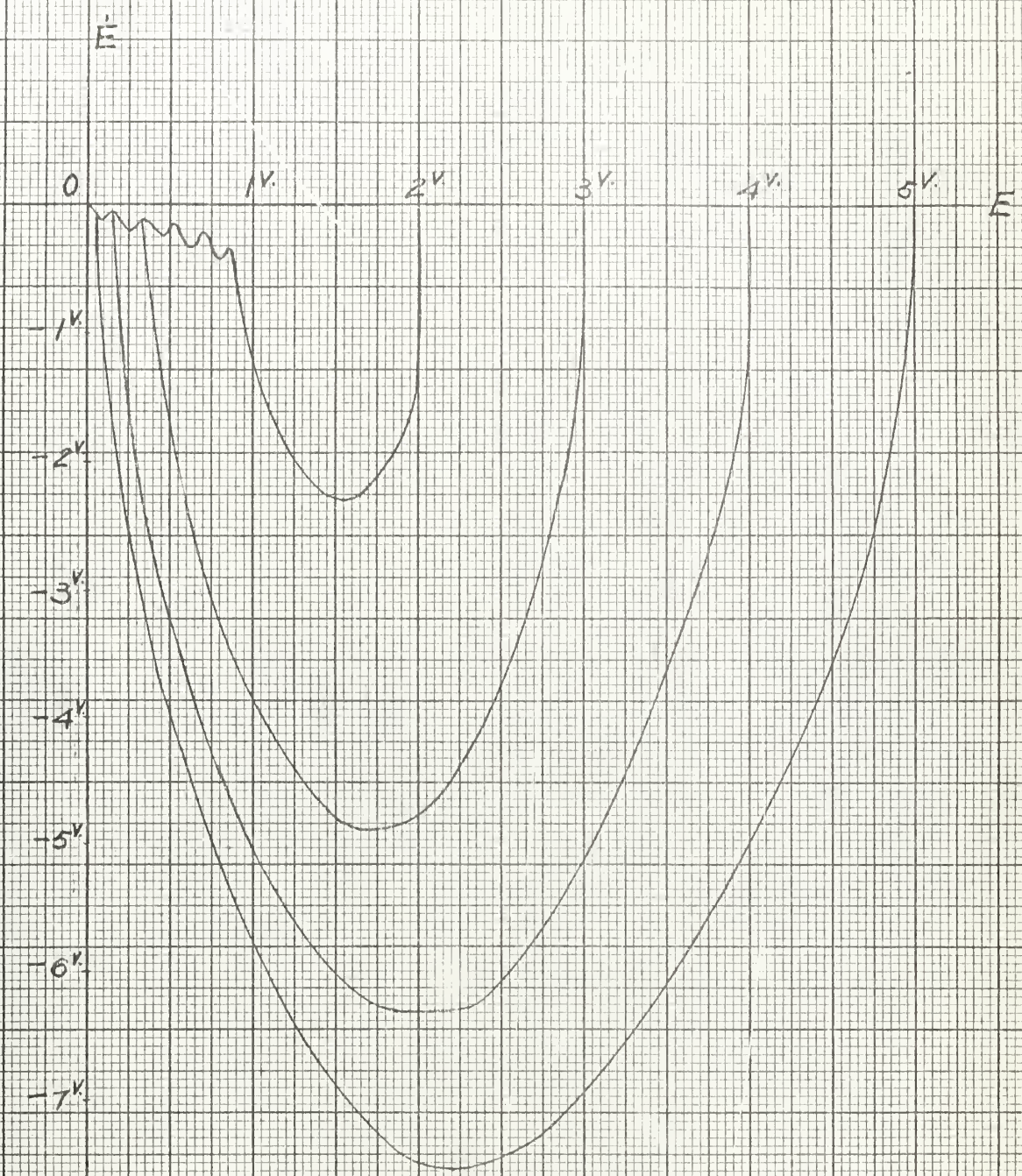


Fig 48 PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 4, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK

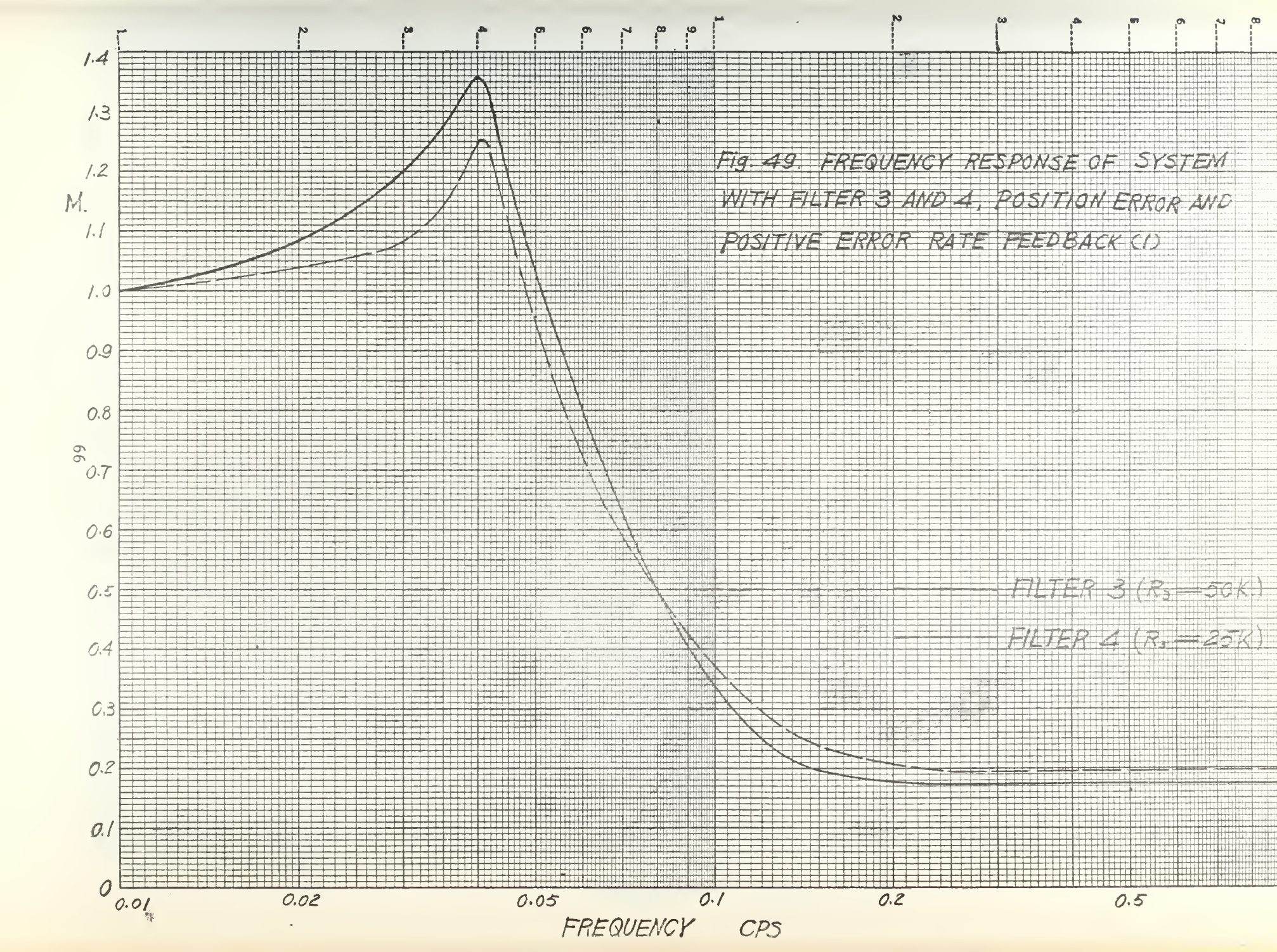


Fig. 49. FREQUENCY RESPONSE OF SYSTEM WITH FILTER 3 AND 4, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (1)

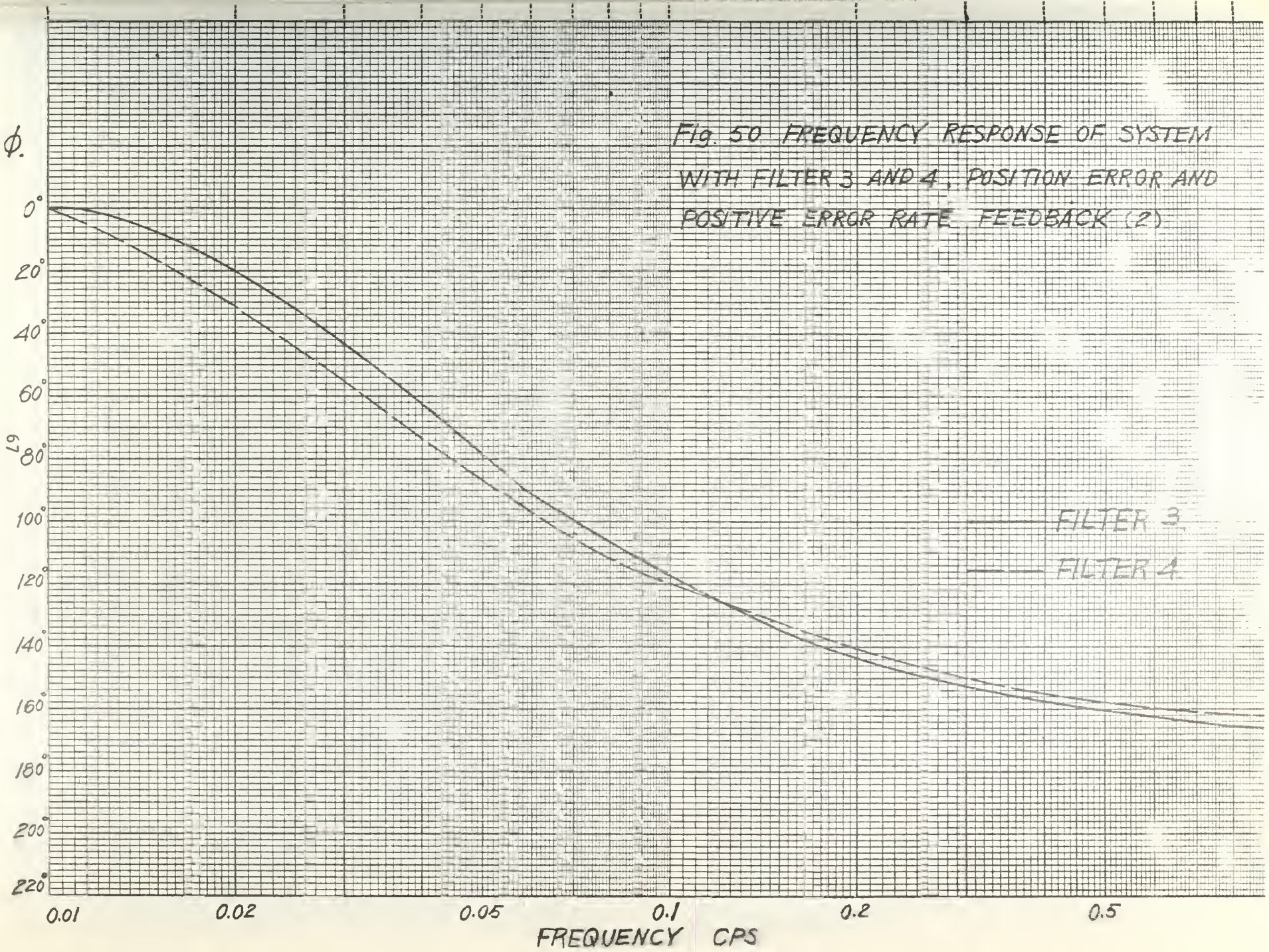


Fig. 50 FREQUENCY RESPONSE OF SYSTEM WITH FILTER 3 AND 4, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2)
φ
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
FILTER 3
FILTER 4
0.01
0.02
0.05
0.1
0.2
0.5
FREQUENCY CPS

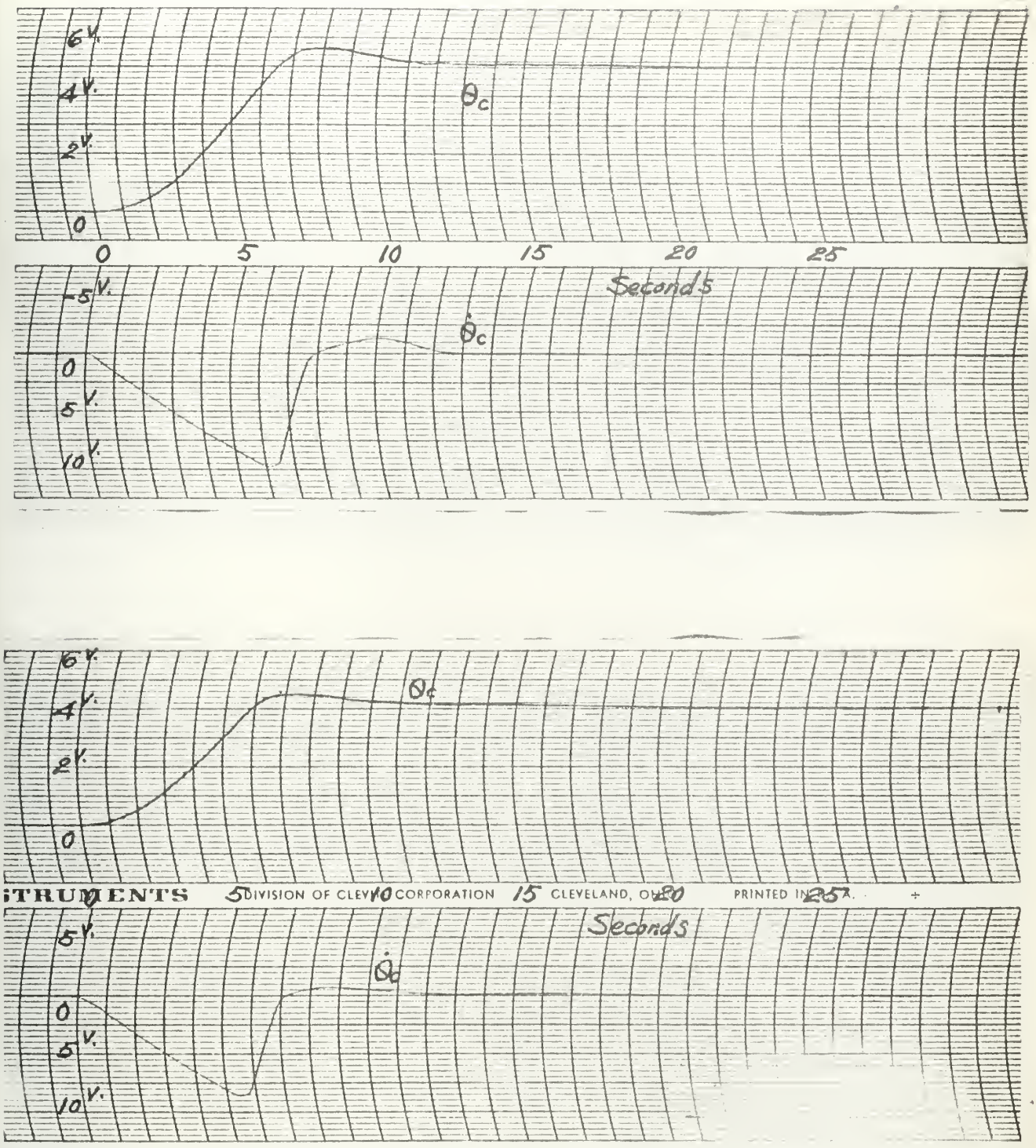


Fig. 51 TRANSIENT RESPONSE OF SYSTEM WITH FILTER 5, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (1).

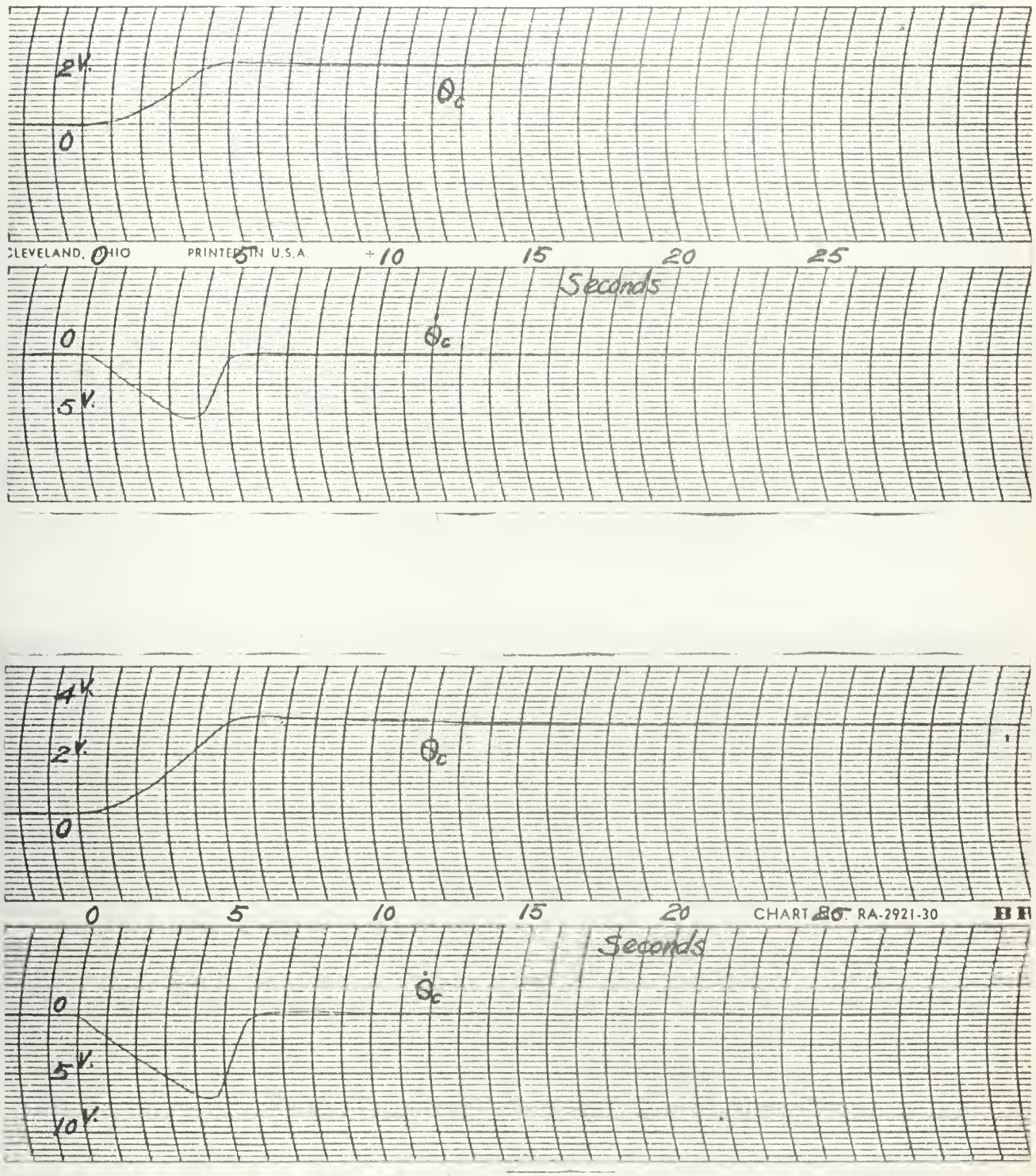


Fig. 52. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 5, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2)

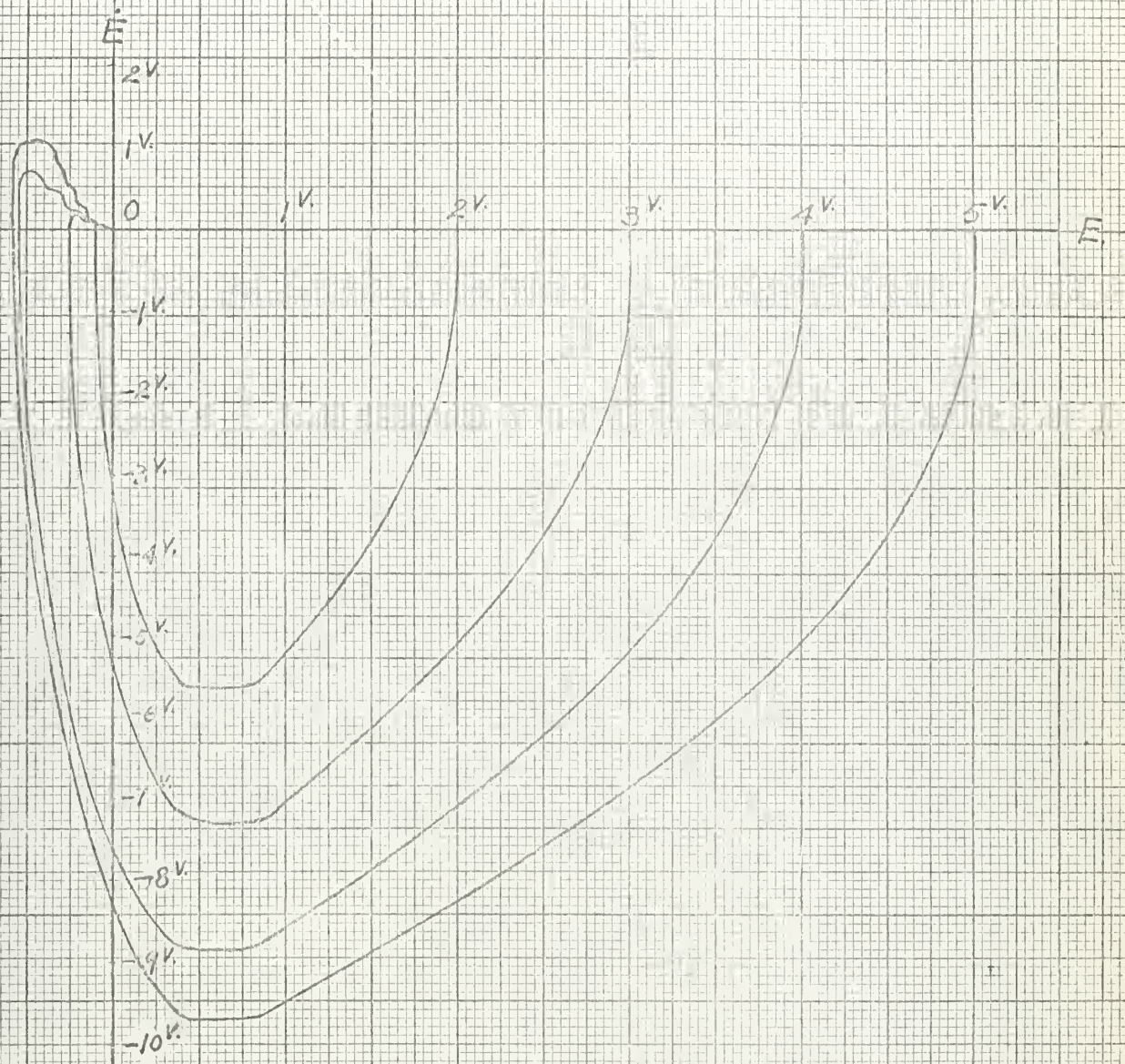


Fig 53. PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 5, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK.

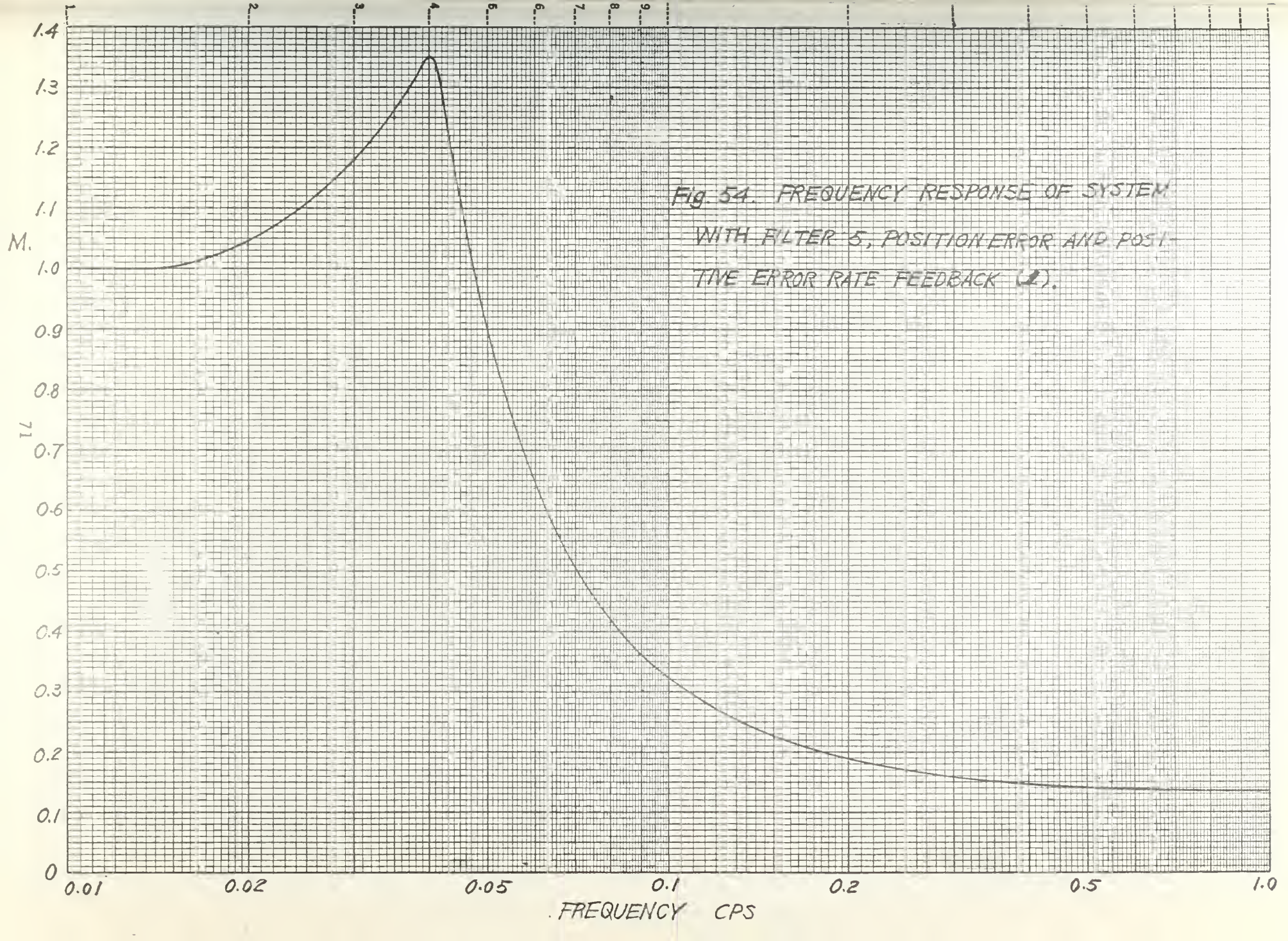


Fig. 54. FREQUENCY RESPONSE OF SYSTEM WITH FILTER 5, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2).

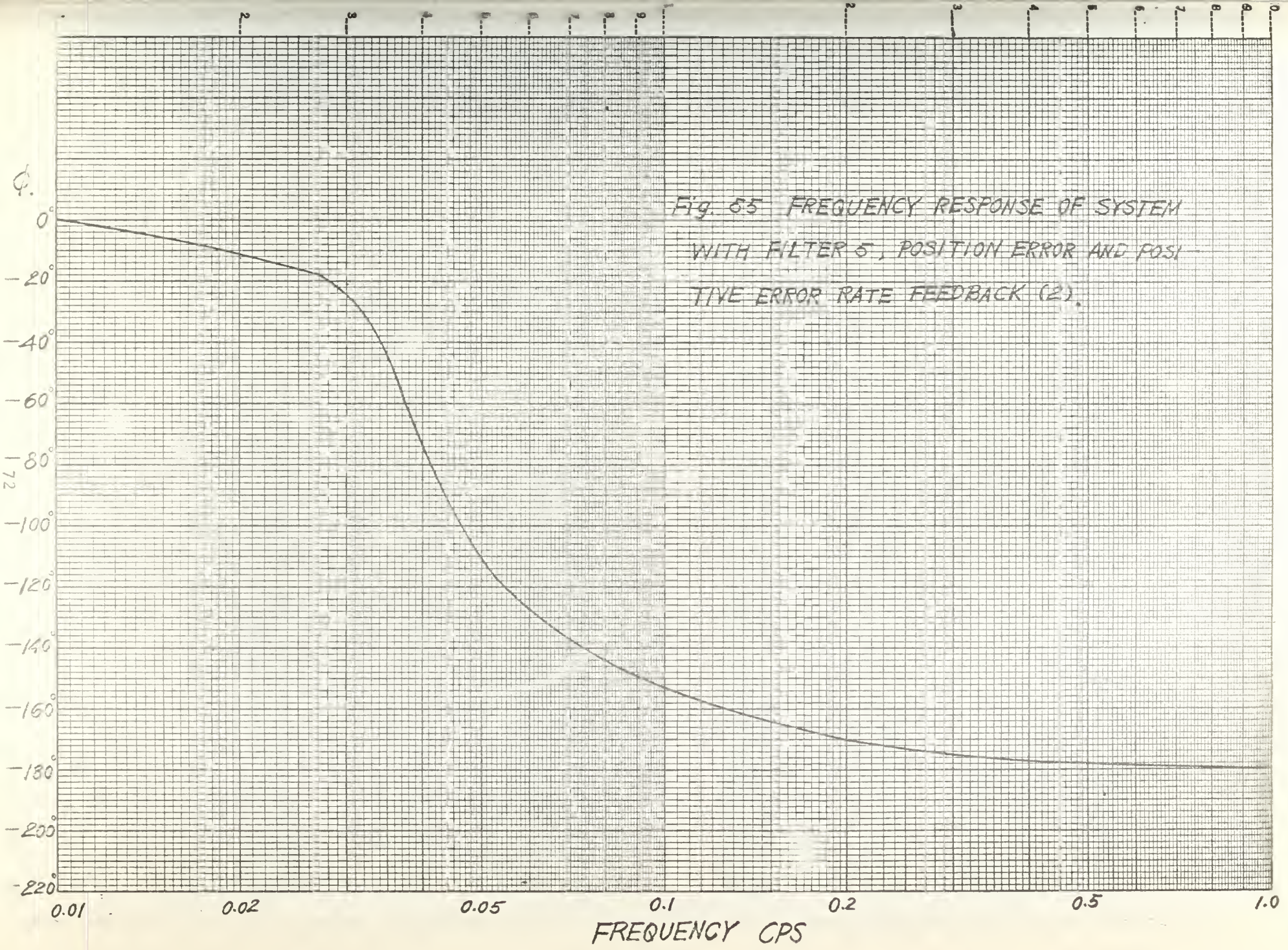


Fig. 55 FREQUENCY RESPONSE OF SYSTEM WITH FILTER 5, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2).

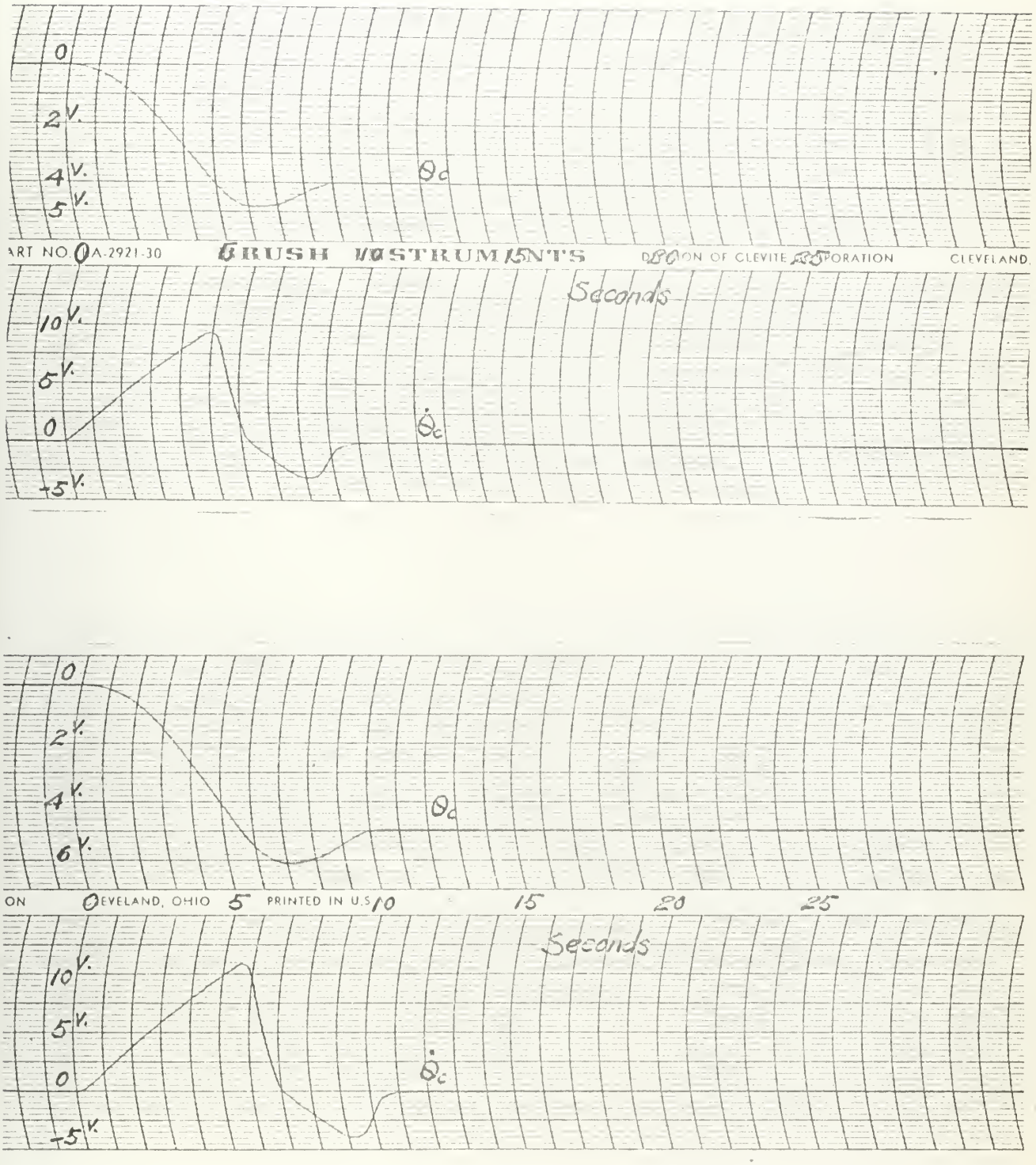
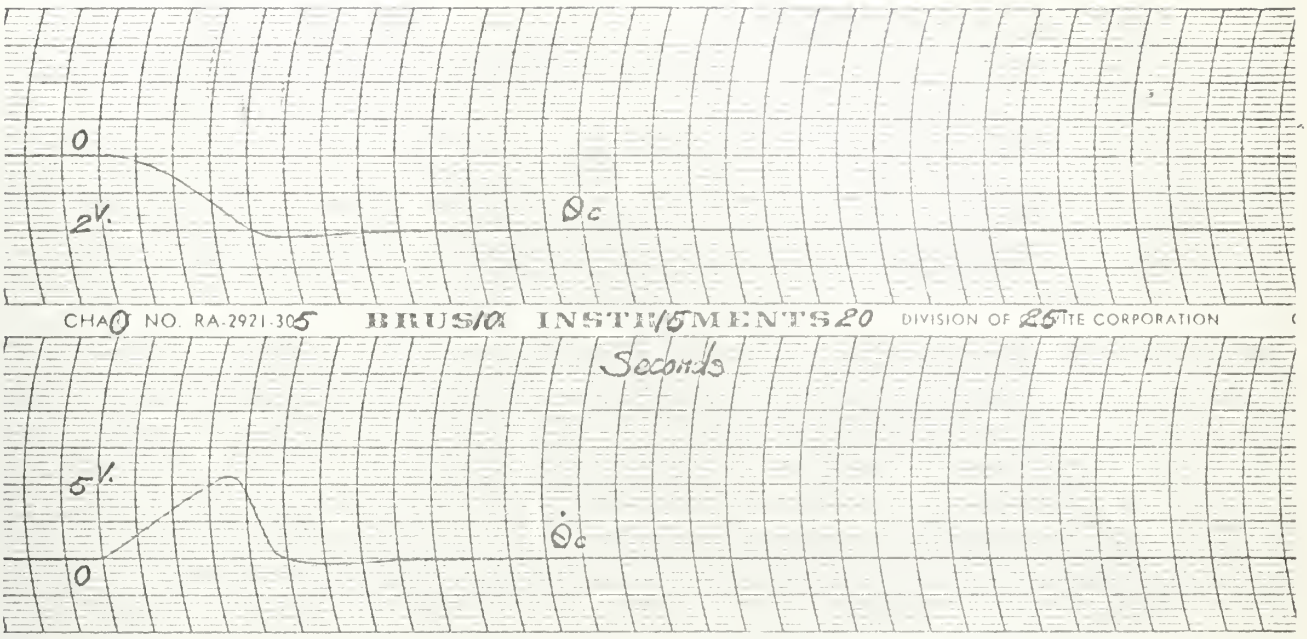


Fig. 56. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 6, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (1).



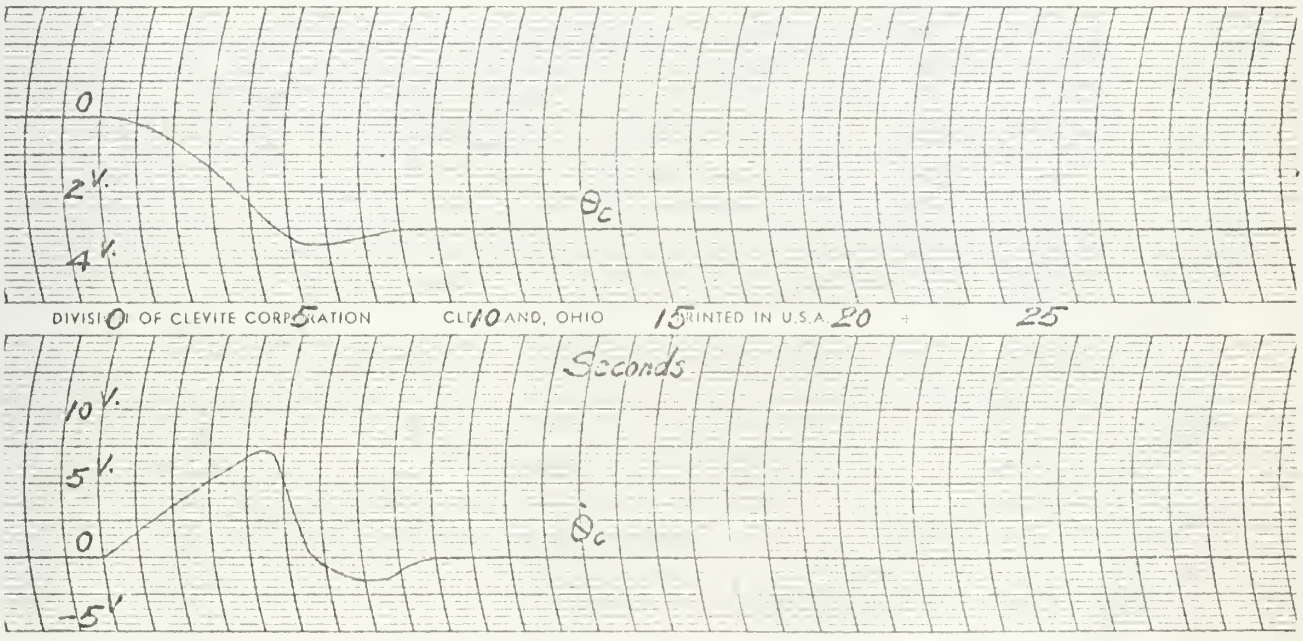


Fig. 57. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 6, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2).

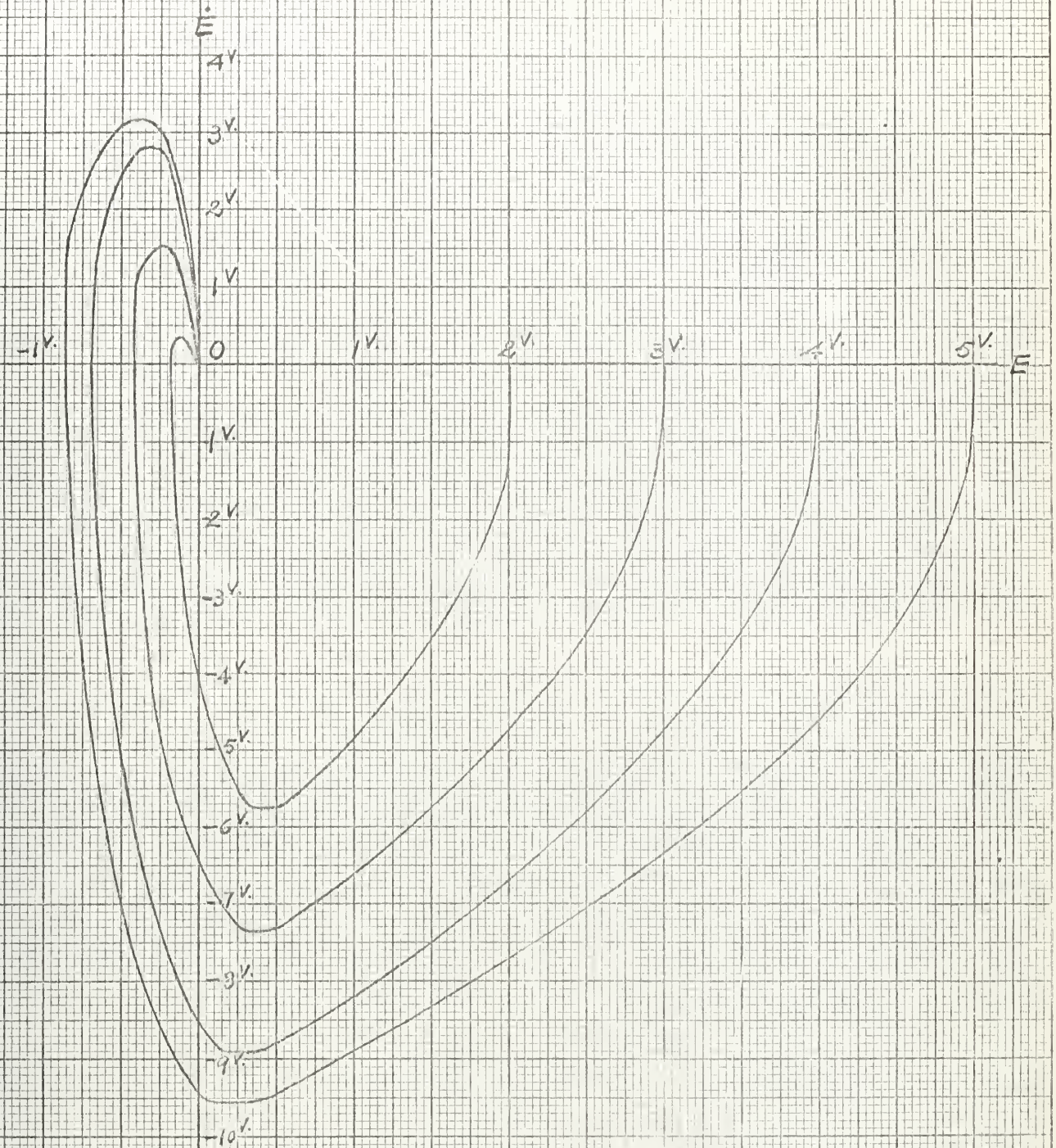


Fig. 68. PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 6., POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK

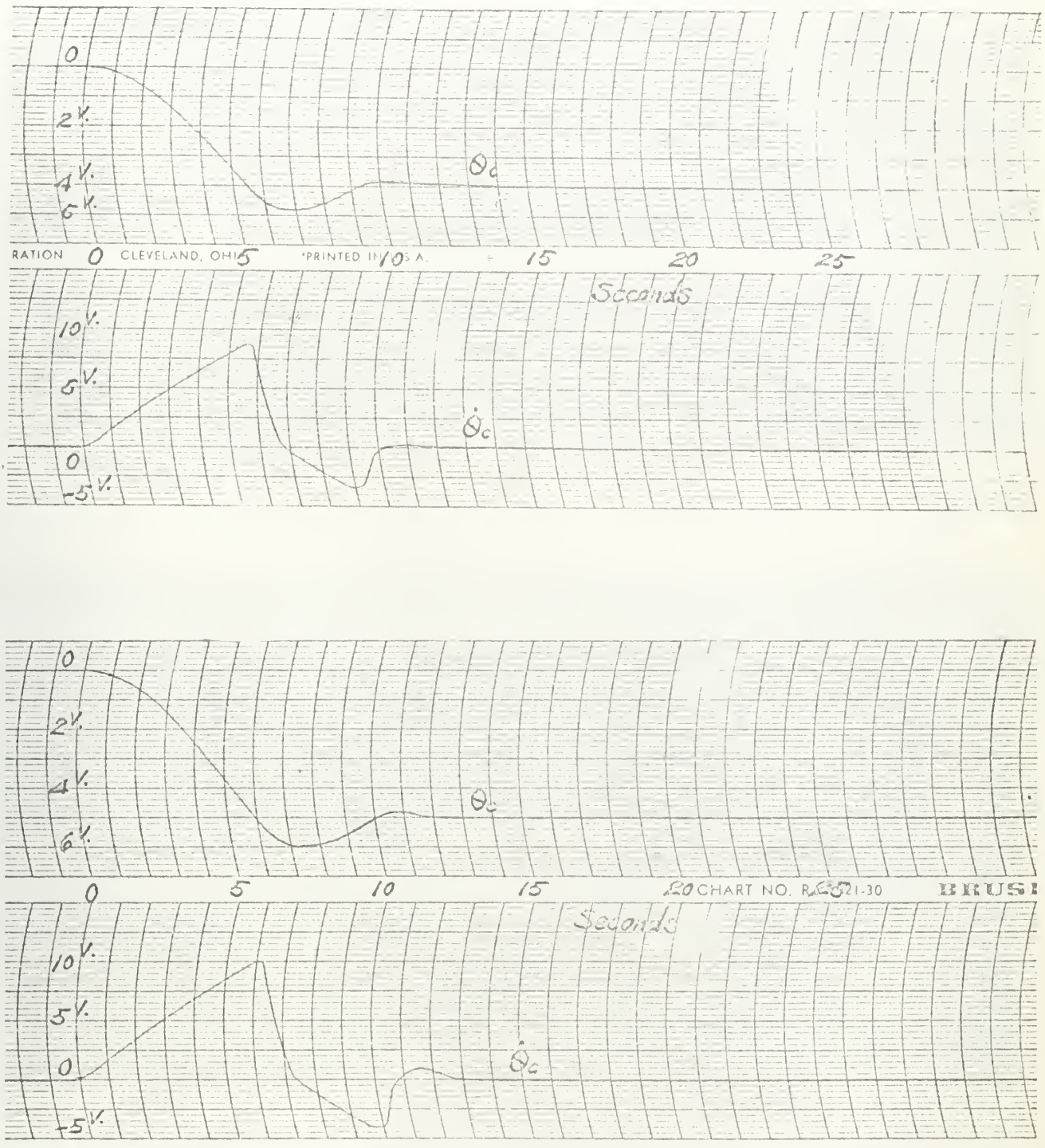


Fig. 59. TRANSIENT RESPOSE OF SYSTEM WITH FILTER 7, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (1).

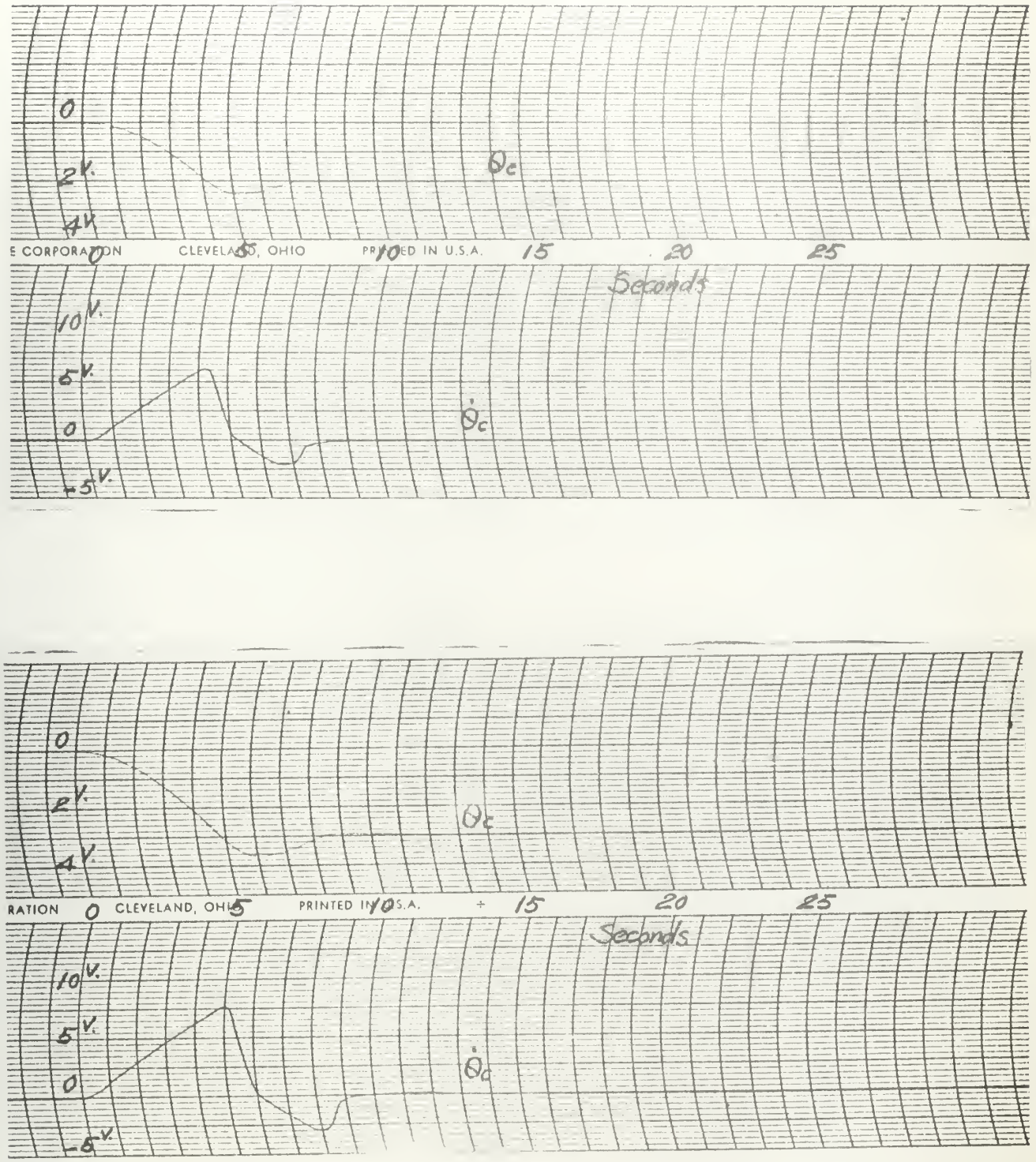


Fig. 60. TRANSIENT RESPONSE OF SYSTEM WITH FILTER 7, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK (2).

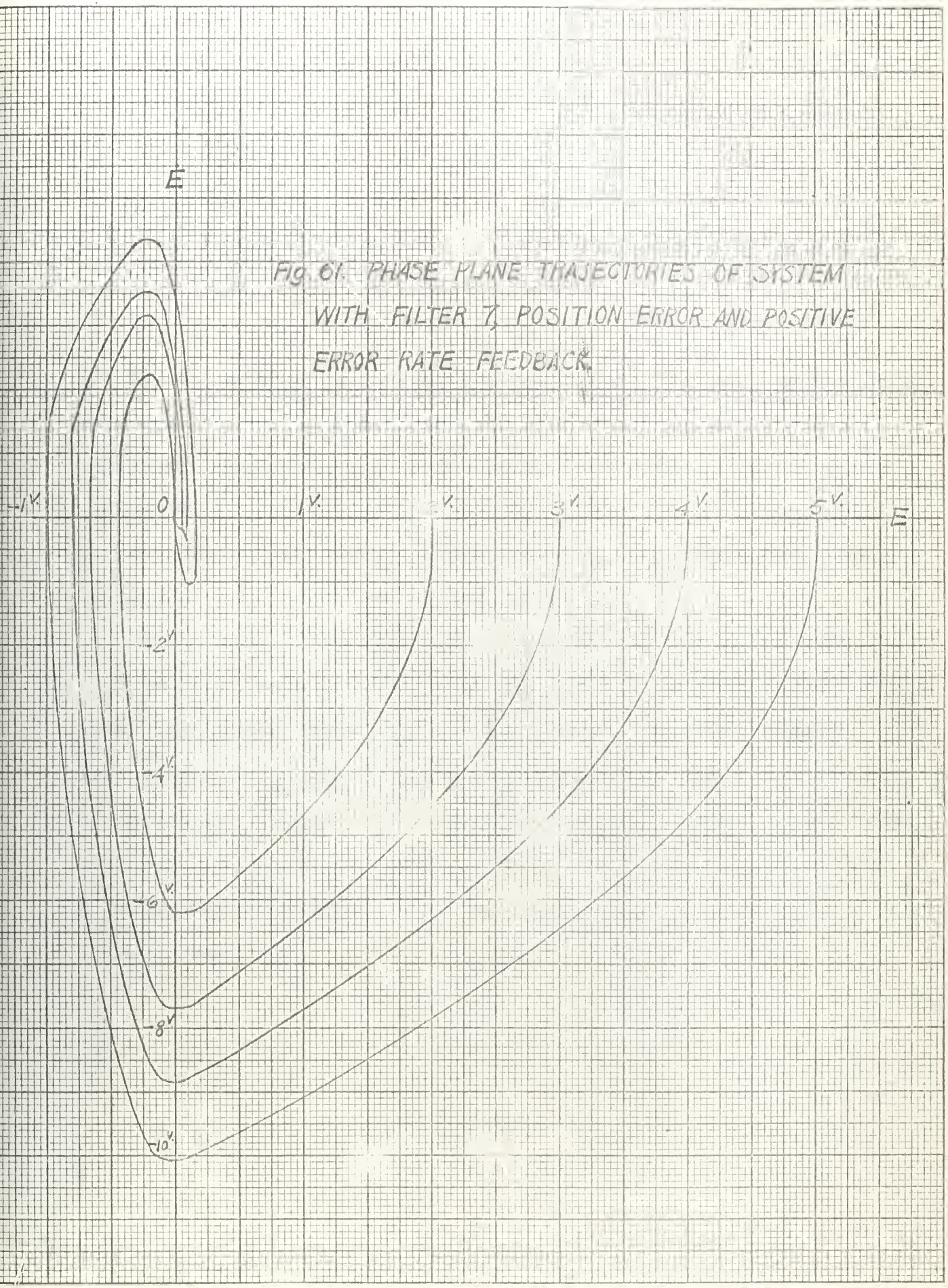


Fig. 61. PHASE PLANE TRAJECTORIES OF SYSTEM WITH FILTER 1, POSITION ERROR AND POSITIVE ERROR RATE FEEDBACK.

8. Comparison of Results

1. The System Responses by Using Different Motor Supply Voltages.

The system transient response [illegible] proportion to motor supply voltage. Since the starting [illegible] motor is proportion to square of supply voltage, therefore the system using a series motor has more sensitive response to applied voltage.

Fig. 62 and Fig. 63 show the transient responses of natural system with various motor supply voltages in 400 cps A. C. Fig. 64 shows the comparison of these transient responses. The transient curve with 90 volts motor supply voltage has fastest response and highest overshoot. On the contrary, the transient curve with 60 volts motor supply voltage has slowest response and lowest overshoot. The step displacement inputs (62.5 degrees) are same for all these tests.

Fig. 65 shows the transient response of natural system with various motor supply voltages in 60 cps A. C. The limit cycles occured when system reach stead state. There are two possible reasons for this phenomenon: First reason, the 60 cps A.C. is not smooth enough to operate such kind of system because the system only operates on half of the cycle. Second reason, the commutators and brushes in D. C. series motor may cause this trouble. So the data beside Fig. 65 are all taken by using 75 volts 400 cps A.C. for motor supply.

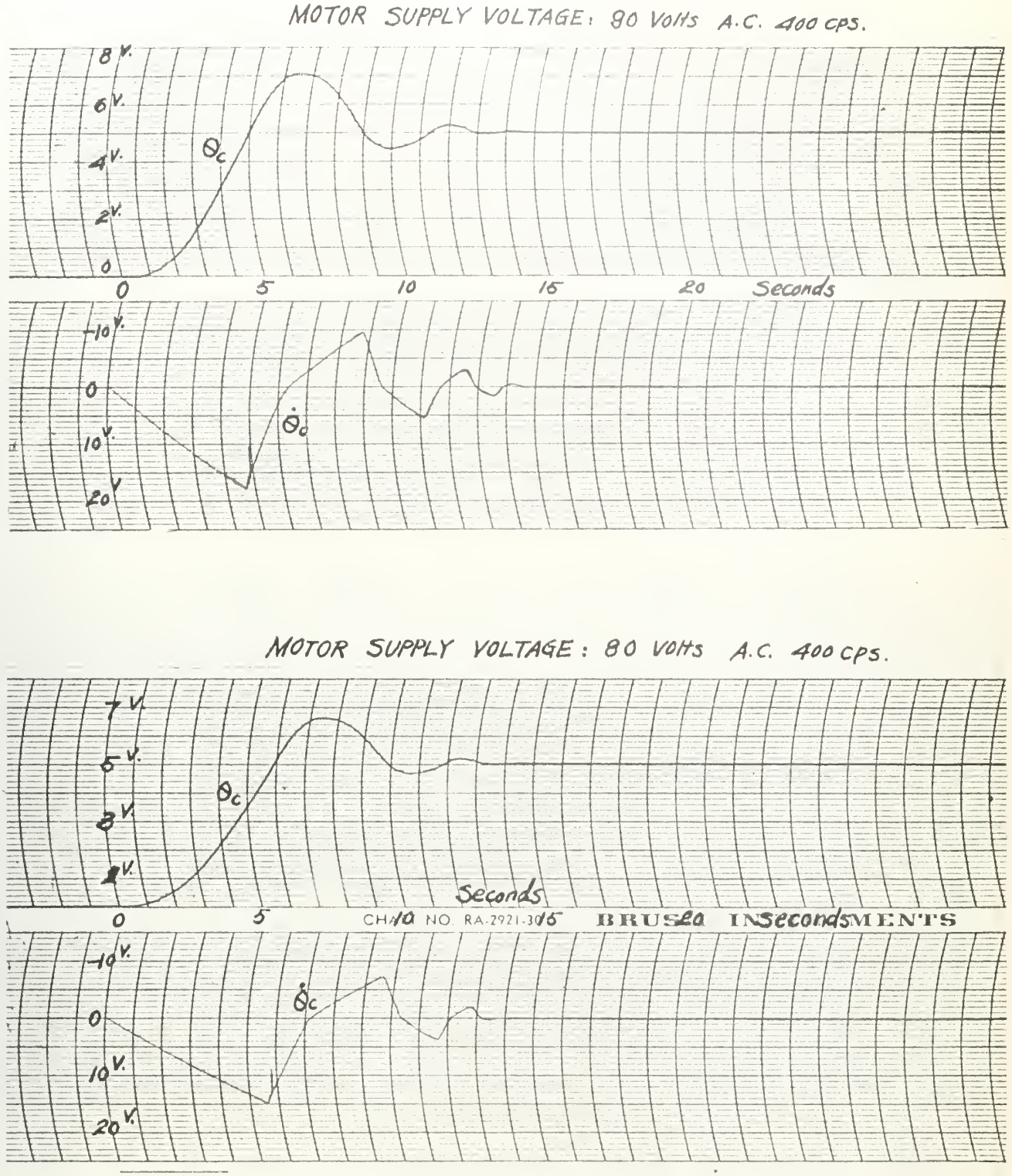
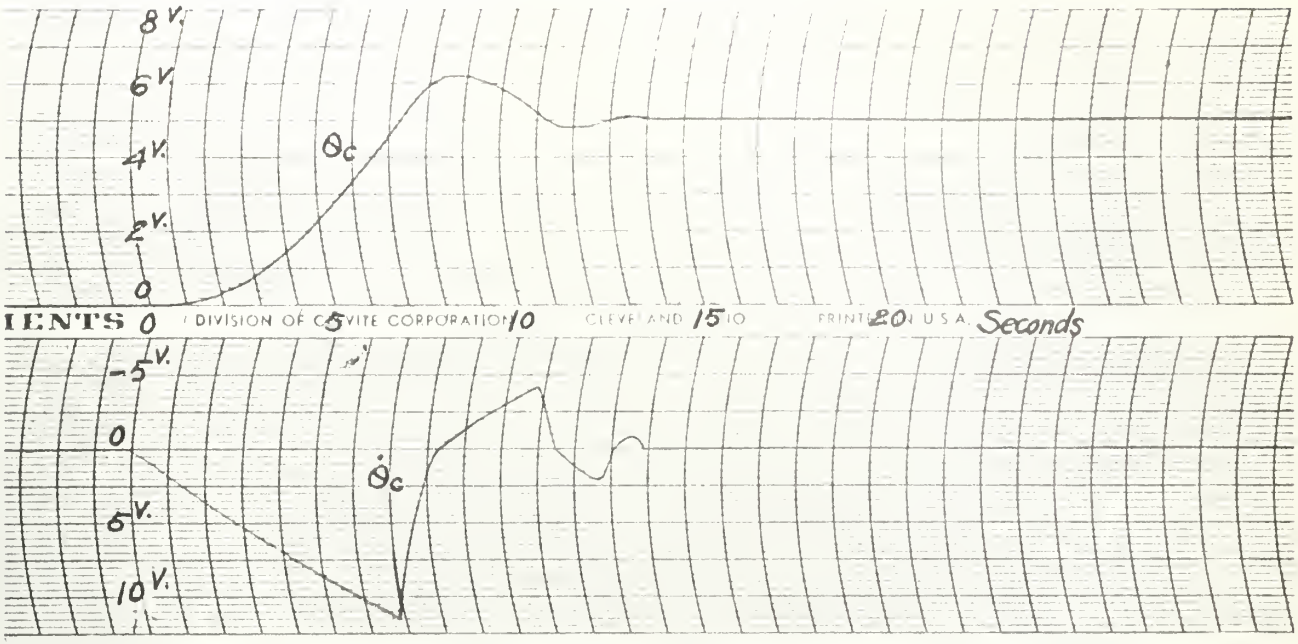


Fig. 62. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR FEEDBACK AND VARIOUS MOTOR SUPPLY VOLTAGE (1)



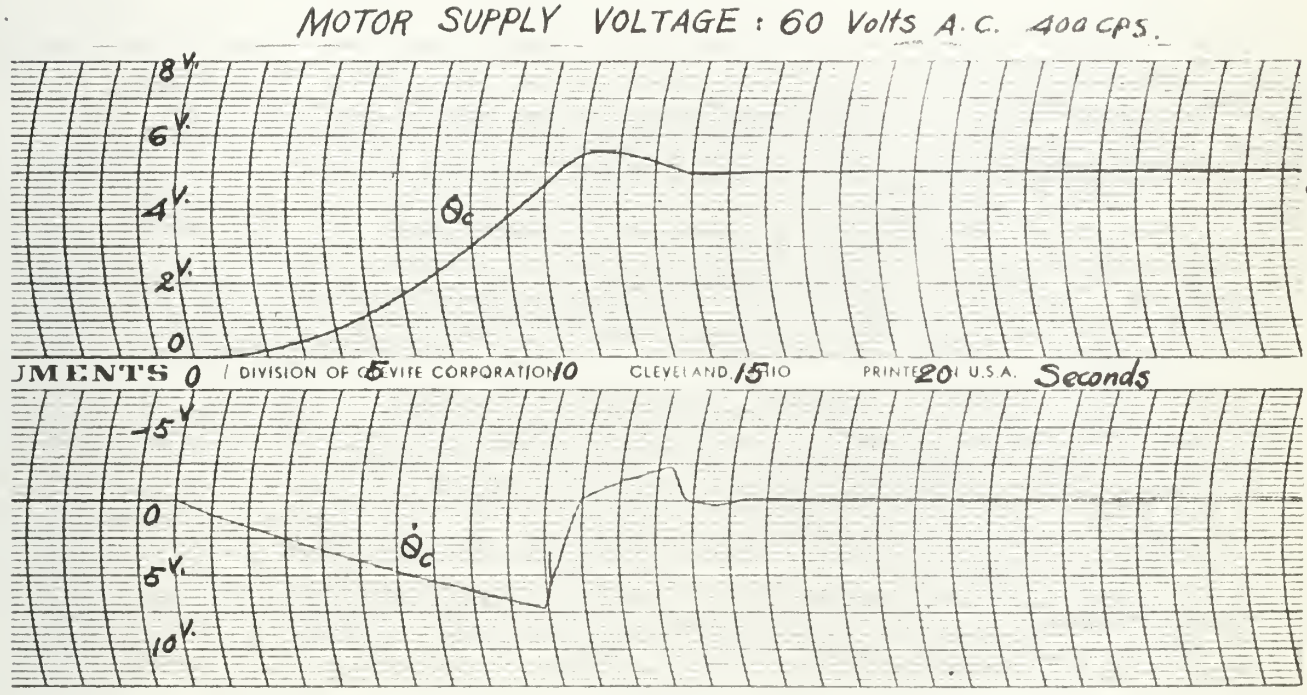


Fig. 63. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR FEEDBACK AND VARIOUS MOTOR SUPPLY VOLTAGE (2).

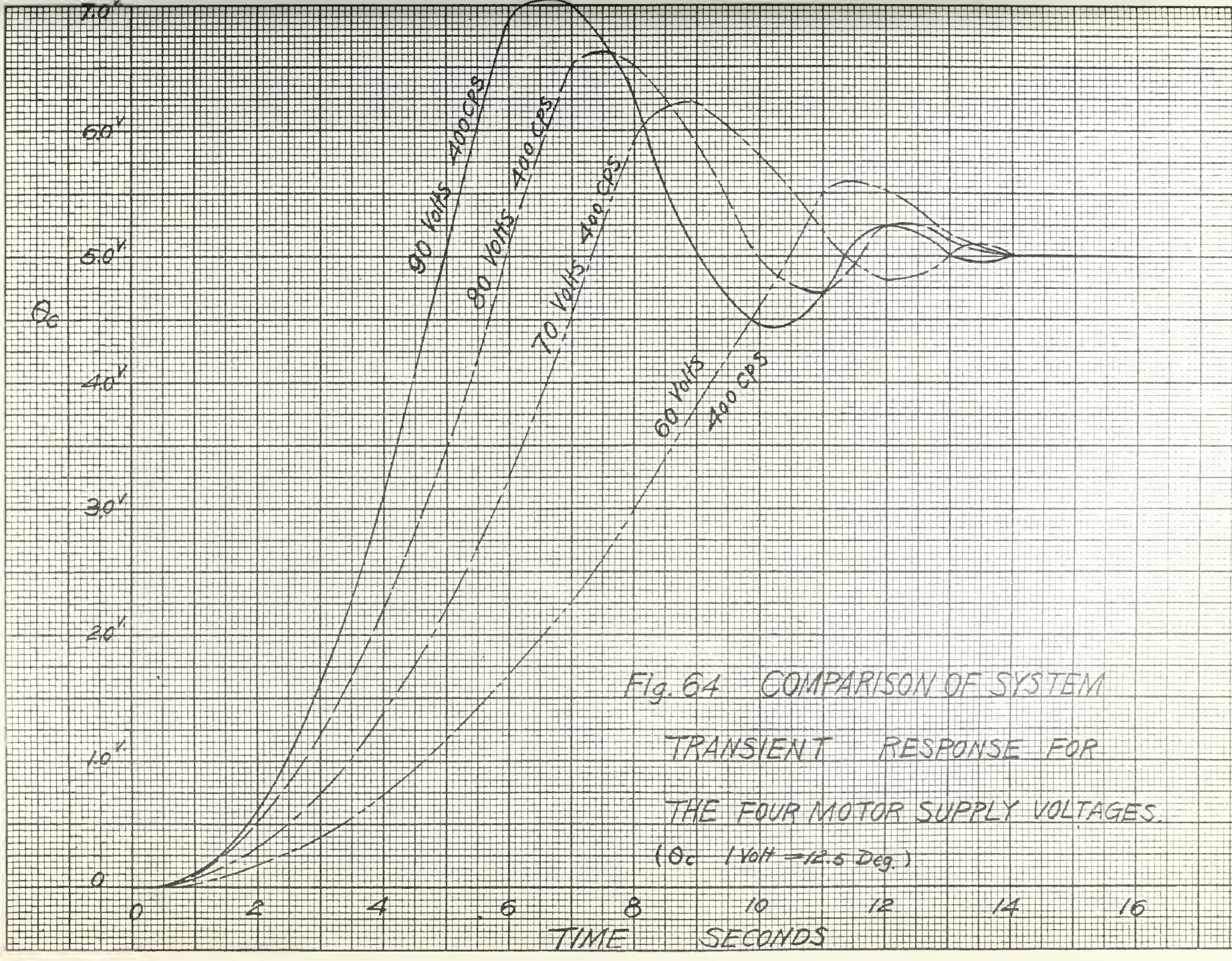


Fig. 64 COMPARISON OF SYSTEM TRANSIENT RESPONSE FOR THE FOUR MOTOR SUPPLY VOLTAGES.

(θc 1 Volt = 12.5 Deg.)

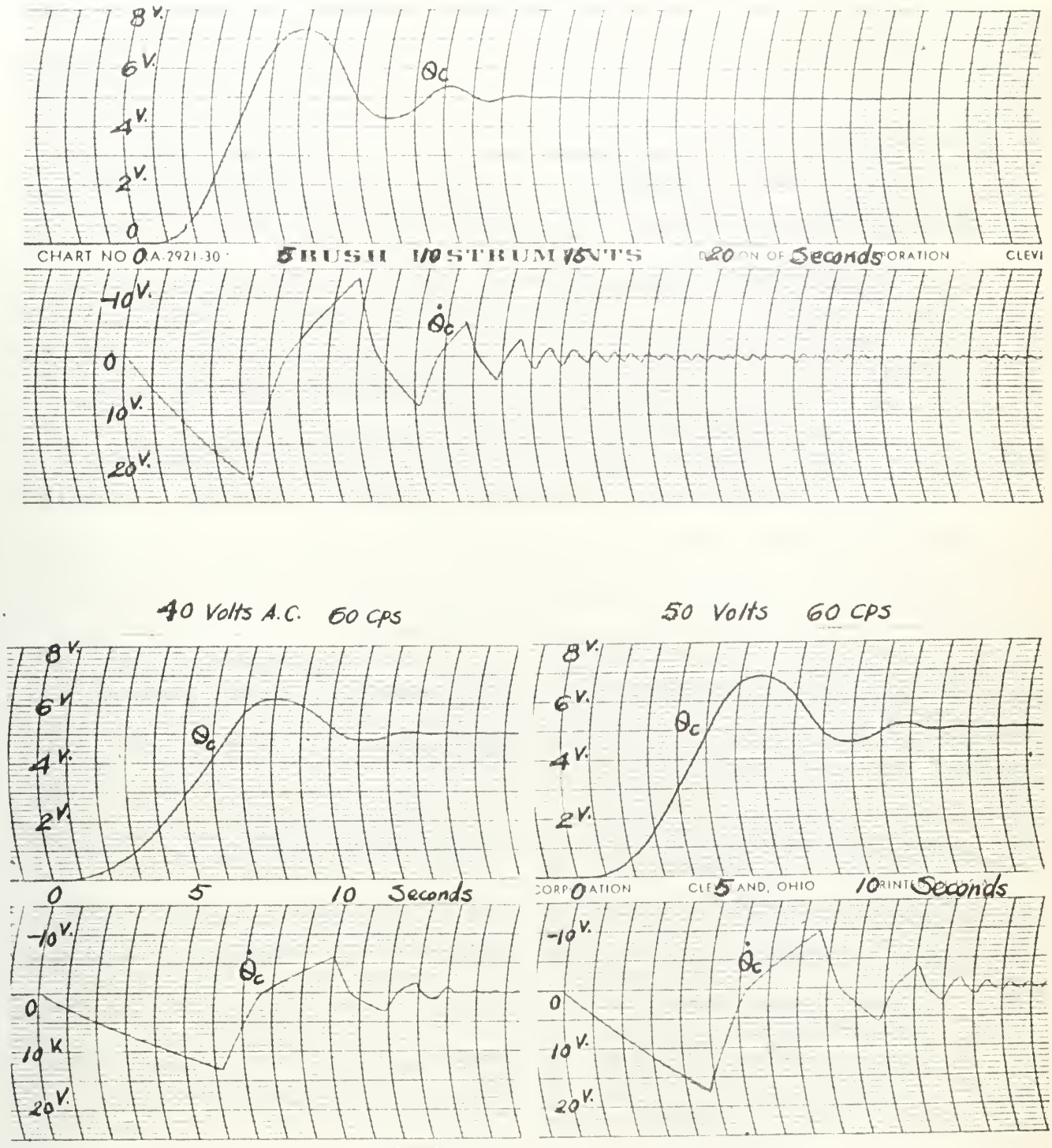


Fig. 65. TRANSIENT RESPONSE OF SYSTEM WITH POSITION ERROR FEEDBACK AND VARIOUS MOTOR SUPPLY VOLTAGE.

2. Comparison of System Response by Using Various Negative Error Rate Feedback:

In section 5 had shown the system optimized response can be accomplished by using properly negative error feedback compensation. Fig. 66 shows the comparison of transient response in these kinds of compensations. The solid line shows the natural system with error feedback. It has highest overshoot and long settling time. When using -0.01667 error rate feedback the percentage overshoot is decreased to 12%. If negative error rate feedback coefficient h over the critical value -0.161, the system will operate as overdamped condition. It takes longest time to reach steady state. The optimized response occurs when feedback coeficient h is equal -0.161. The system will have fastest response and no overshoot, and Fig. 67 shows their phase plane trajectories.

The switch line shifting angles are indicated in it. The chattering phenomenon occuring in overdamped condition is clearly shown in Fig. 67.

The system frequency responses are also effected by error rate feedbacks. The system has less overshoot at resonance frequency and fast response in transient when it has optimized error rate feedback. There is no resonance frequency when h-0.611 is used for feedback compensation. The comparison of system frequency response is shown in Fig. 68.

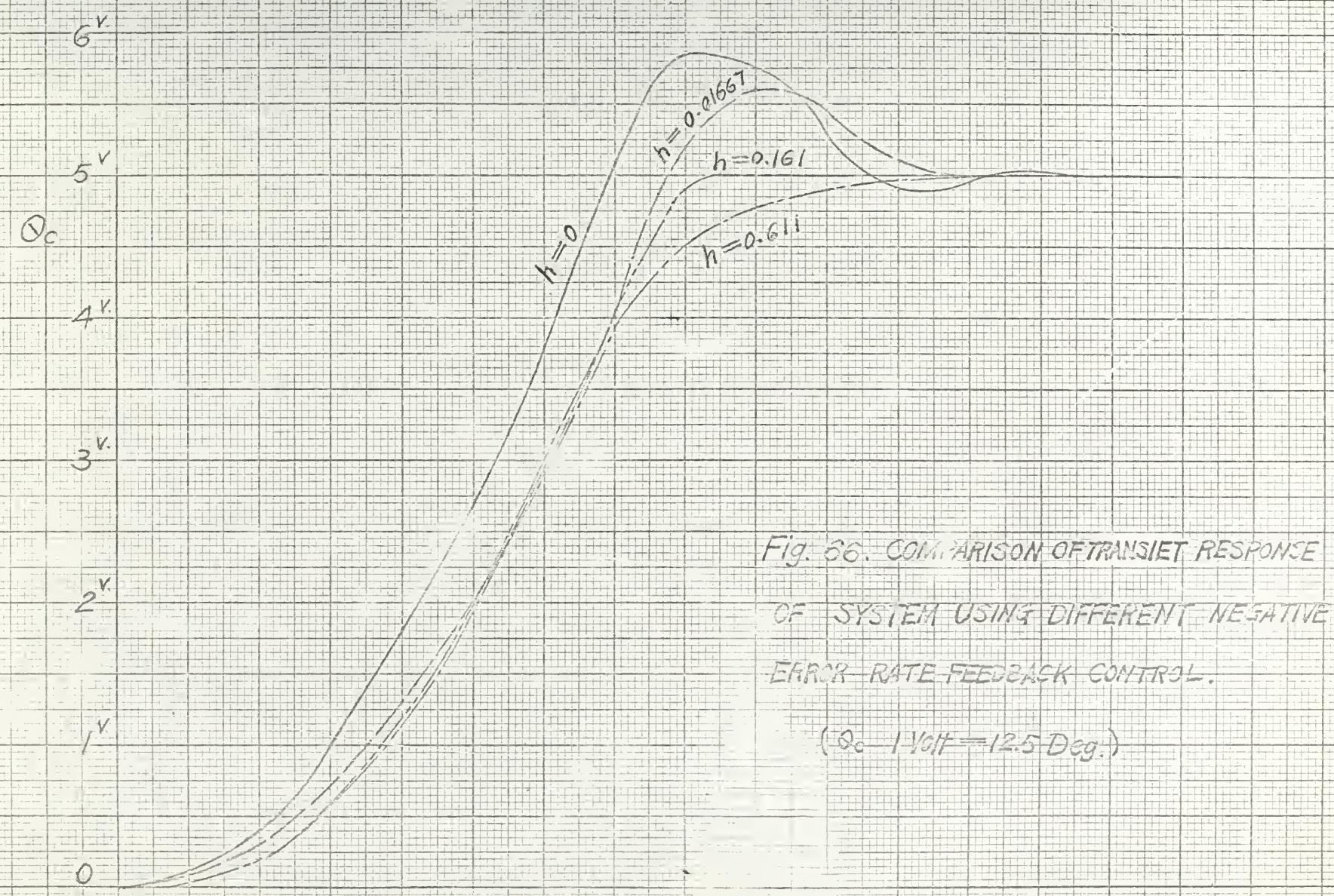


Fig. 66. COMPARISON OF TRANSIET RESPONSE OF SYSTEM USING DIFFERENT NEGATIVE ERROR RATE FEEDBACK CONTROL.

(θ_c 1 Volt = 12.5 Deg.)

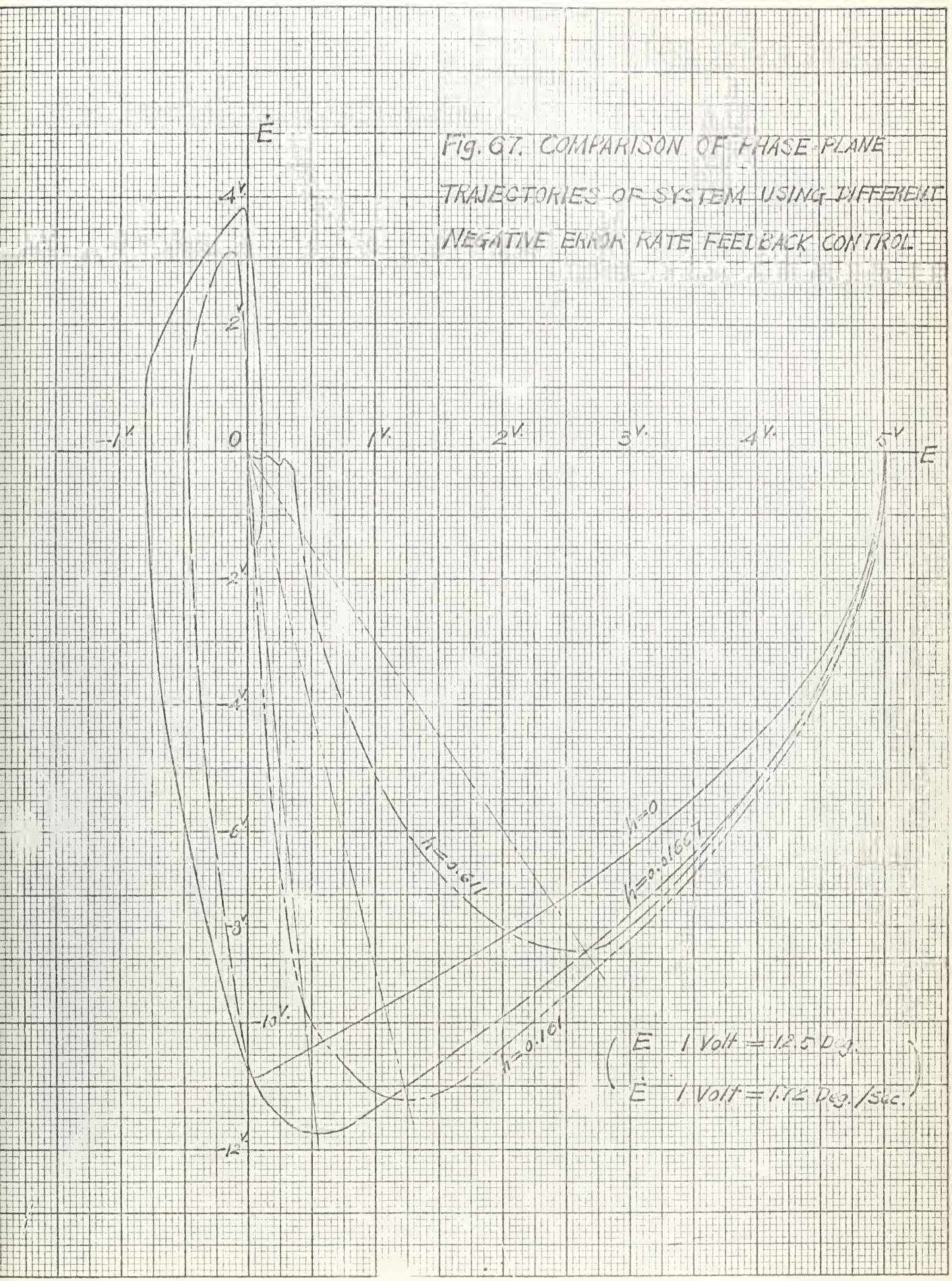


Fig. 67. COMPARISON OF PHASE PLANE TRAJECTORIES OF SYSTEM USING DIFFERENT NEGATIVE ERROR RATE FEEDBACK CONTROL.

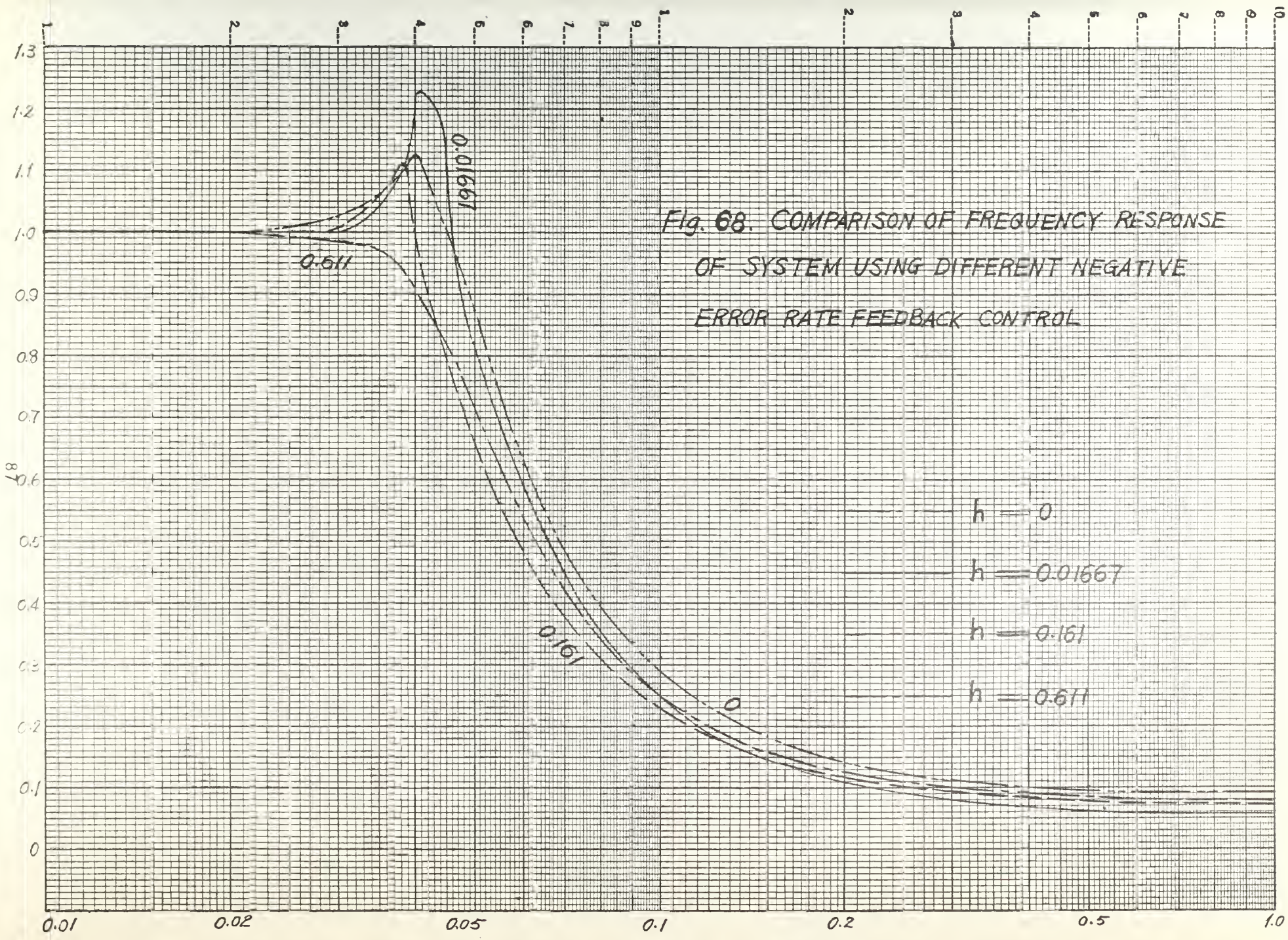


Fig. 68. COMPARISON OF FREQUENCY RESPONSE OF SYSTEM USING DIFFERENT NEGATIVE ERROR RATE FEEDBACK CONTROL

3. Comparison of System Response by Using Various Filters Compensation:

Fig. 69 shows the comparison of system transient response with various filter compensation. The compensated systems all have less overshoot than uncompensated system with positive error feedback. When proper filter is used for compensation the system will have fastest response and no overshoot. The system with Filter 1 compensation has such ideal response.

The comparison of phase plane trajectories is shown in Fig. 70. The chattering phenomenon will occur if the filter rotates the switch line angle too large or too small. The solid line indicates the trajectory of natural system with positive error rate feedback. The trajectories of system with Filter 1, compensation has shortest path to reach origin. It has the fastest response compared to other filter compensation.

Fig. 71 shows the comparison of system frequency response by using three different but typical filters for compensation. The system with Filter 1 compensation has highest overshoot at resonance frequency. The other two filter compensations also have higher overshoot than natural system with positive error rate feedback.

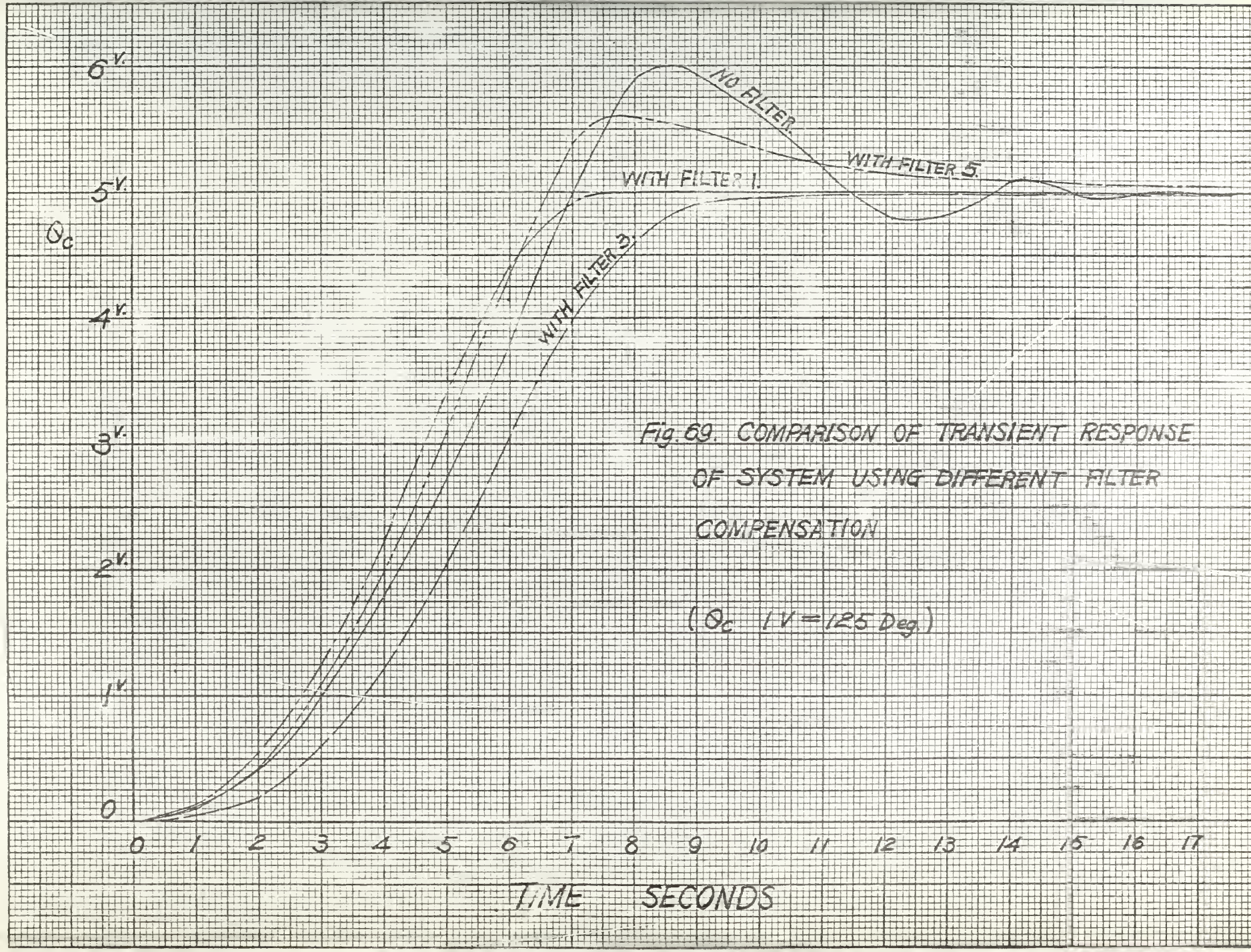


Fig. 69. COMPARISON OF TRANSIENT RESPONSE OF SYSTEM USING DIFFERENT FILTER COMPENSATION

(θ_c 1 V = 125 Deg.)

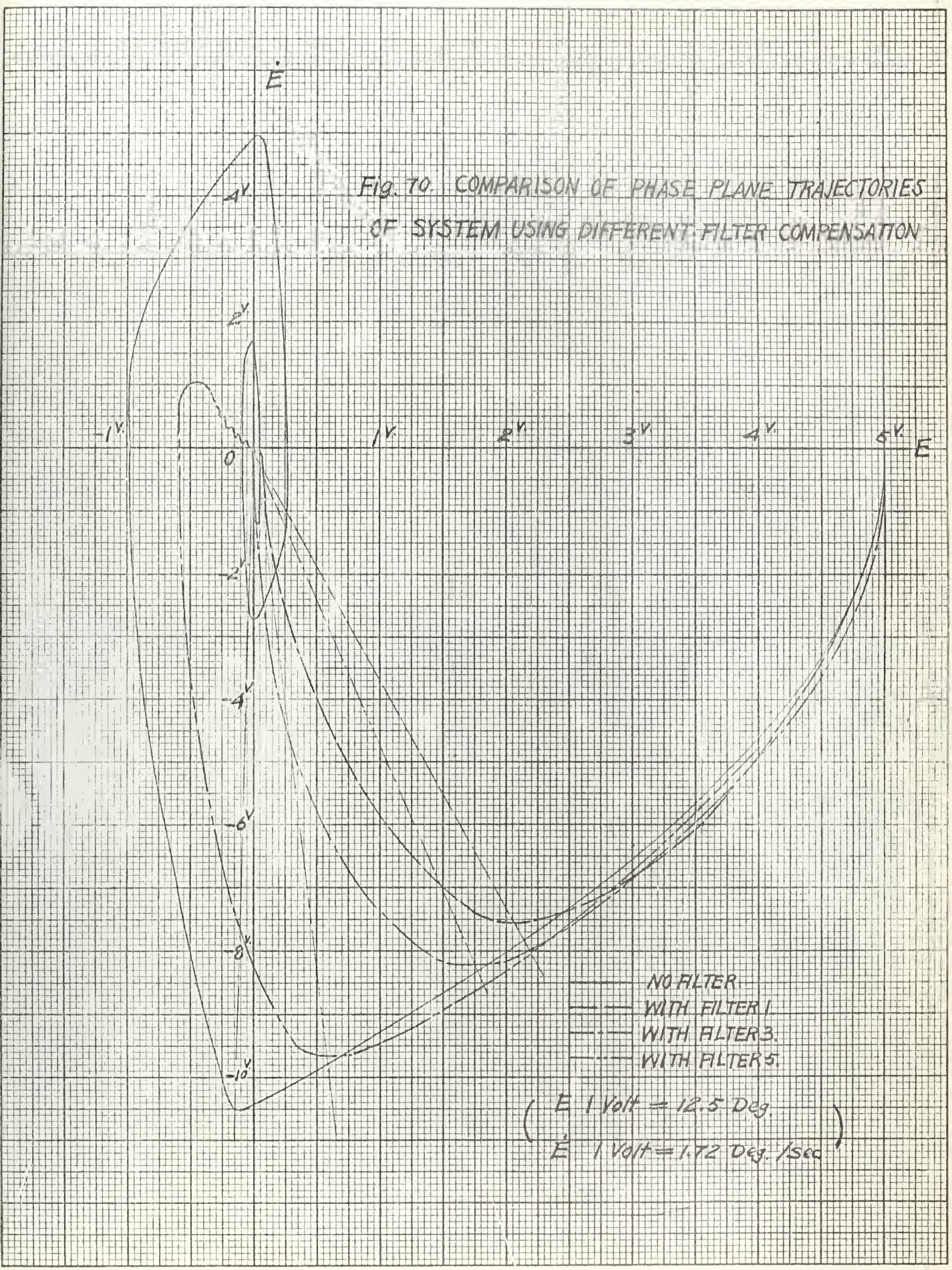


Fig. 70. COMPARISON OF PHASE PLANE TRAJECTORIES OF SYSTEM USING DIFFERENT FILTER COMPENSATION

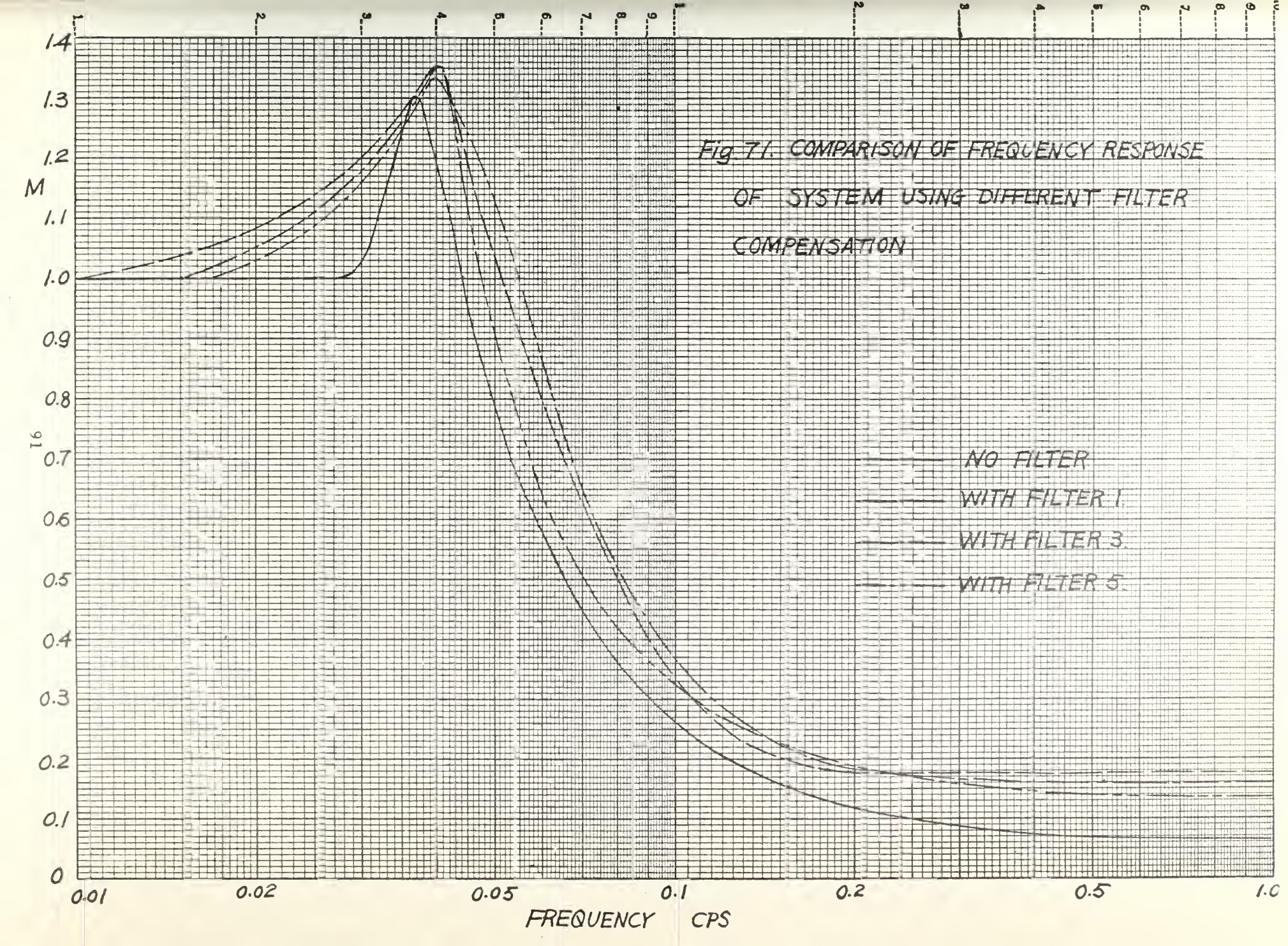


Fig 71. COMPARISON OF FREQUENCY RESPONSE OF SYSTEM USING DIFFERENT FILTER COMPENSATION

9. Conclusions and Recommendations

The transistorized relay servo controller has been design and got good results by using a D. C. series motor in the experimental system. It is concluded that:

1. The compact construction of design transitorized relay servo controller should not only save materials cost but, more important for system engineering reduce development cost and save space and weight.

2. Since transistorized relay does not have contact arcing problem it will increase the relay servo system reliability. Even in high altitudes it's still in normal operation condition.

3. The small dead zone in transistorized relay will increase the system steady state accuracy.

4. The split field series motor, with its current squared torque characteristic, provides an ideal method of driving a transistorized relay operated servomechanism where fast response is required.

5. The series motor with its transistorized controller has been tested by applying different A. C. voltages.

6. Optimum response to different size step displacement input was obtain by error and negative error rate feedback.

7. By using filter compensation network, the experimental system can obtain optimum response.

8. Linear relay switching criteria has been studied and applied in experimental system.

By limiting of time, the author can not work farther by apply controller in shunt motor and two phase servo motor. It is recommended that:

1. Further study be made of the transistorized controller to control shunt (separate field) motor and two phase servo motor forming a relay servo system.

2. Its extension to higher order system study is quite encouraging.

3. The transistorized flip-flop circuit can be used as switch in relay servo, provide the system allowable for small limit circle but no switch's dead zone.

4. Dual-Mode transistorized relay servo may be design for it fast response characteristic. The feedback loop across the relay can make this kind of system no steady state error; even input is very small.

10. Bibliography

1. G. J. Thaler, Nonlinear Servomechanisms, Chapter C, Relay Servomechanisms, pp c27-c33.

2. G. J. Thaler, Elements of Servomechanism Theory, McGraw Hill, 1955.

3. Floyd E. Nixon, Principles of Automatic Controls, Prentice-Hall, Inc.

4. Richard B. Hurley, Junction Transistor Electronics, "D. C. Amplifier." Wiley

5. Chester L. Dunsmore, "Computer Analogs for Common Nonlinearities," Control Engineering, Oct. 1959.

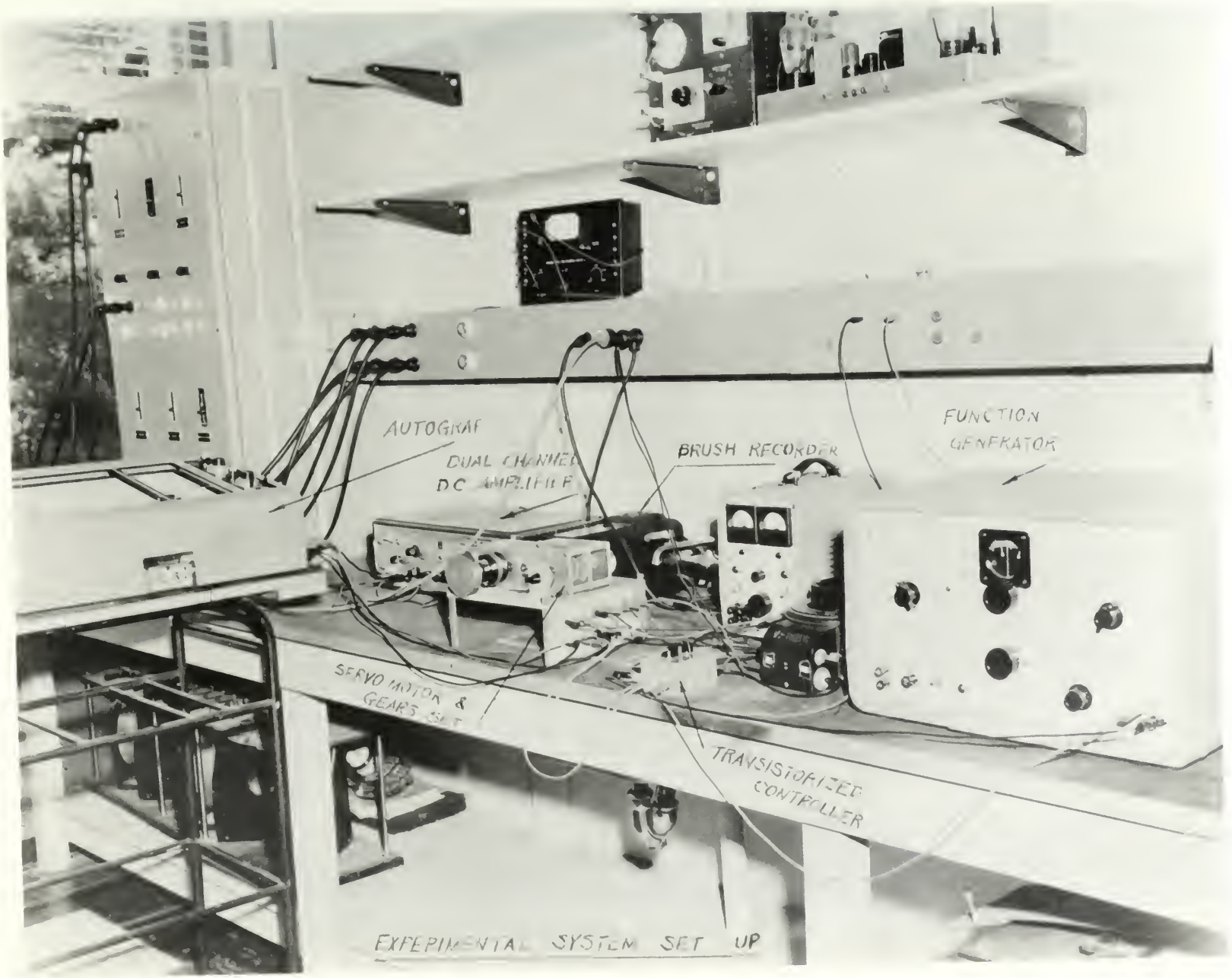
6. E. H. Cooke Yarborough, An Introduction to Transistor Circuits, New York, Interscience Publishers, Inc. 1951.

7. Archie P. Stockebrand, "An Experimental Study of Relay Servo Optimization using a Series Motor," (Masters thsis, U. S. Naval Postgraudate School, Monterey, Calif. 1959).

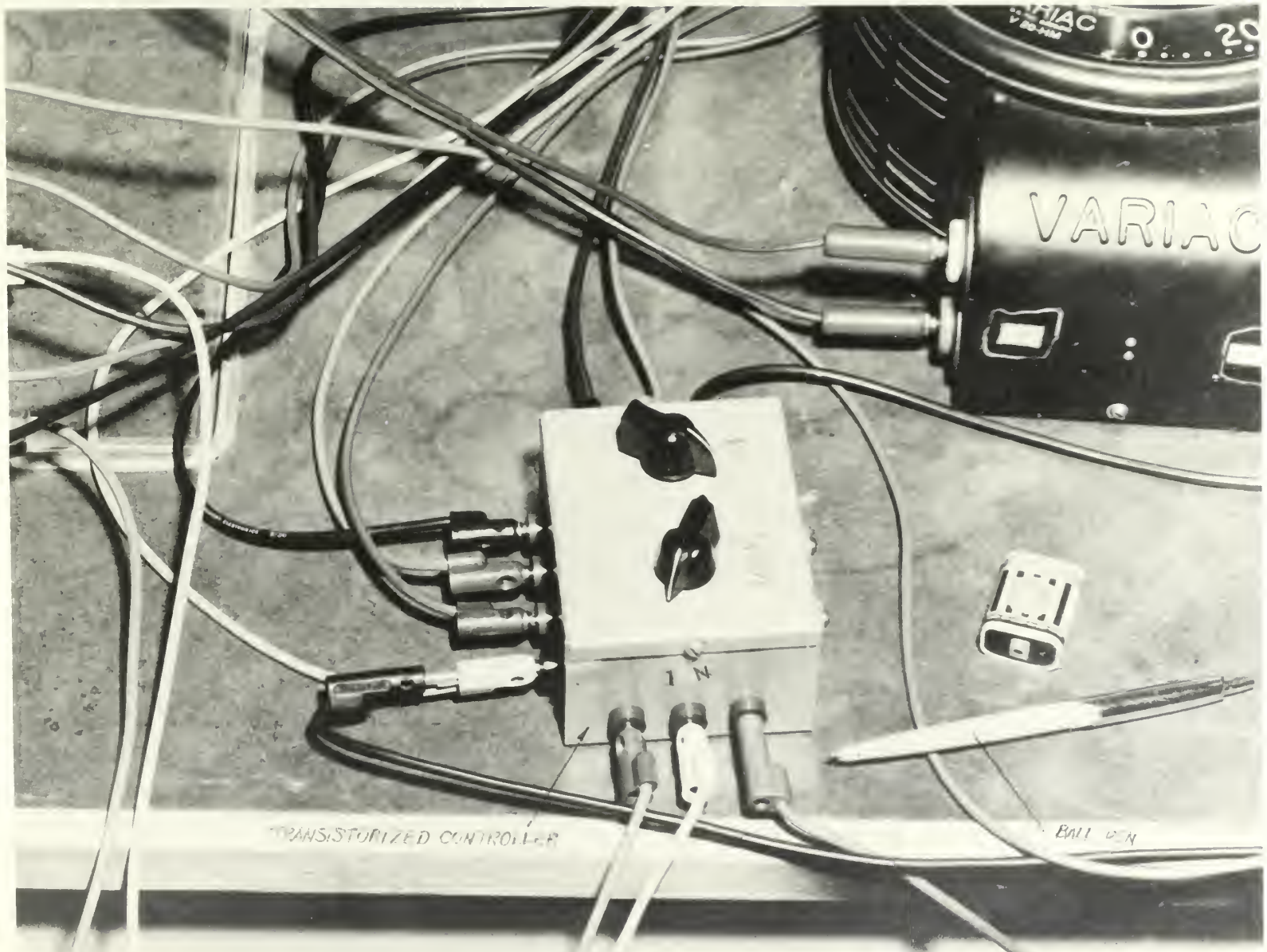
8. Chen and Little, "Standard Transistorized Optimum Response Controller, Applications and Industry, pp. 337-340.

9. G. E. Transistor Manual, Third Edition, G. E. Company.

10. Notes on the Application of the Silicon Controlled Rectifier, G. E. Company.



EXPERIMENTAL SYSTEM SET UP



PHYSICAL APPEARANCE & RELATIVE SIZE OF TRANSISTORIZED CONTROLLER

thesL713
Transistorized relay servo optimization
3 2768 001 03389 7
DUDLEY KNOX LIBRARY